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A COMPREHENSIVE STUDY OF POSSIBLE SOLAR ACTIVITY  
INFLUENCE ON THE UPPER STRATOSPHERE AND MESOSPHERE

by

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## Abstract

A comprehensive program of research was conducted to study possible influence of solar activity on the upper stratosphere and mesosphere (25-90 km).

The indices of solar activity whose possible influence were examined are:

1) the AE index, a measure of global electrojet activity, 2) the magnetic storm index  $D^{st}$ , 3) the solar radio noise flux at 10.7 cm wavelength  $F_{10.7}$ , 4) 1-10 Mev and 60 Mev solar proton flux as measured by satellite, 5) solar magnetic sector boundary crossings, 6) solar magnetic sector intensities, as measured by field strength, temperature, density and speed of the solar wind, 7) the Zurich sunspot number, 8) the cosmic ray flux as measured by ground based neutron monitor count, and 9) large flares, as measured by the new comprehensive solar flare index. The meteorological parameters whose possible influence by solar activity were studied are: 1) departures of measured temperature, density, pressure, zonal wind, and meridional wind from "climatological" monthly means, 2) the magnitude of gravity waves and planetary waves, as deduced by the daily difference analysis method, 3) weekly stratospheric circulation index and thickness values for the  $30^{\circ}$ - $70^{\circ}$  latitude zone between pressure heights of 5 mb and 0.4 mb. Some analyses were done by the "superposed epoch" method (e.g., solar sector boundary crossings and flare occurrences which relate only to timing) while others were done by cross correlation techniques (e.g., solar sector intensities which are both magnitude and time dependent).

With these data, several hypotheses for possible solar activity influence on the upper stratosphere and mesosphere could be tested, including: 1) direct heating by ozone absorption of UV or by high energy particle flux, 2) cooling because of decreased ozone due to higher nitric oxide production by solar fluxes and/or cosmic rays, 3) increased gravity wave or planetary wave activity due to reflection condition changes above 65 km (or decreases due to reflection below 25 km), as proposed by Hines, and 4) standing wave pressure perturbations of the type hypothesized by Volland. Of the many solar activity correlations examined, somewhat more than the expected number were found to have indicated significance better than 1%. However, no convincing case could be made from these data for any of the specific solar activity influence hypotheses examined.

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## 1. INTRODUCTION

### Solar Activity Influence on the Thermosphere

Interest has long been given to the question of possible solar activity influences on the weather, atmospheric conditions, and related atmospheric phenomenon. Until the early 1960's, few conclusions concerning the subject could accurately be drawn, due to the previous inadequacies of the available data bases. Satellites, relaying precise measurements of many thermospheric conditions at somewhat regular intervals, enabled researchers to study in detail the influence of solar and geomagnetic indices on these atmospheric parameters. Beginning with Nicolet's (1963) explanation of the thermopause temperature regulation in connection with solar radio fluxes, the field has continued to broaden. Within a year, Jacchia (1963) pointed out a correlation between the 27 day periodic density oscillations and solar electromagnetic radiation, while solar corpuscular particle bombardments in the thermosphere were found to be responsible for the even longer semi-annual density oscillations. In addition to the 27-day density oscillation relationship, Jacchia (1970) noted that the 27-day solar rotation period was reflected in the temperature variations of the upper atmosphere as well. Harris and Priester (1965) observed a definite correlation between thermospheric temperature changes and electromagnetic solar radiation in the 120 to 1500 km range. Through an analysis of satellite drag data, even shorter-term temperature fluctuations have been cited as being associated with variations in geomagnetic activity by Chandra and Krishnamurthy (1968). The response of winds in this region to both increased geomagnetic and solar activity has been investigated by Hicks and Justus (1970) as well. While it is not to say that further research problems do not exist regarding solar activity influence on the ionosphere, the data obtained to this point has been extensively analyzed, and an understanding of the mechanisms which control atmospheric conditions above 100 km has been derived and well documented.

### Possible Solar Activity Influence on the Lower Atmosphere

The link to couple solar activity and the variations in its respective indices with the weather and meteorological phenomenon in the lower atmosphere has been sought even more feverishly, perhaps due to the social, cultural, and

economic values involved should solar activity influence prove highly significant. Strong correlations between solar activity and the variations of many parameters in the surface to 25 km region have been claimed, but the confidence intervals of these correlations are seldom analyzed.

Numerous correlations between tropospheric meteorological patterns and solar parameters are readily found, but the results are rarely accompanied by a plausible mechanism. The apparent influence of both the single and double sunspot cycle on the amount of annual rainfall is discussed by King (1975). Thompson (1973) and Roberts (1974) have shown an apparent correlation between the number of droughts and the sunspot minimum. At the 500 mb level, Zerefos (1974) also found that circulation patterns strengthen after strong solar events. The apparent effect of solar corpuscular streamers on both the troposphere and stratosphere is reviewed by Mustel (1968).

Roberts and Olsen (1973) suggested one of the few solar-meteorological hypothesis for the troposphere. They propose that increased solar particle ionization in and around the troposphere could, after producing nucleation which forms a cirrus deck, lead to a heating of the upper troposphere. Zerefos (1975) on the other hand, is in support of Schuurmans' (1969) model that utilizes the solar flare index, because he himself found a distinct change in tropospheric temperature following the highly energetic Type IV solar proton events.

Wilcox, with the introduction of the solar magnetic sector structure, opened a new era in the search for solar-weather relationships. Solar sectors are divisions of the solar magnetic field which alternate in magnetic polarity. The solar wind, a carrier of ionized particles which sweeps radially outward from the sun, and the solar magnetic field vary in phase with each other with the magnetic field intensity reaching a maximum value about one day after the passage of each solar sector boundary and gradually weakening throughout the sector. Heath, et al. (1975) found that enhancements of solar UV irradiance were more closely associated with the central meridian passage on the solar surface than with sector boundary passage at the earth (there being about a 4-1/2 day lag between the former and the latter). Fougere (1974) has found, however, that unlike the post 1963 solar sector structure which has been determined from satellite data, the pre 1963 solar sector structure, inferred from polar magnetometers indicates low solar and geomagnetic activity

in the positive (away) sectors, and high solar and geomagnetic activity in the negative (toward) sectors. These results cast doubt on the early magnetometer inferred sector structures (for this study only post 1963 sector structure data will be used).

Using a superposed epoch analysis Wilcox, et al. (1974) in the best substantiated statistical argument yet, claims a 10% hemispheric vorticity area index response to the solar sector structure at the 300 mb level. Roberts and Olsen (1973) earlier found a 40% effect on individual trough vorticity area index. The use of solar sectors in an analysis has a definite advantage over geomagnetic indices, since the latter, although strongly correlated with solar disturbances, also contain meteorologically induced components through upward transport of energy from the troposphere into the ionosphere (Hines, 1973). Herman and Goldberg (1978, p. 215) have attempted to discredit this idea by pointing out that magnetic storms which appear to precede vorticity-area changes have fluctuations of several hundred gamma, whereas the meteorologically induced components should be no more than 3-6 gamma in magnitude.

Summaries of these and numerous other sun-weather relationship studies are given in the Proceedings of the Symposium on Possible Relationships Between Solar Activity and Meteorological Phenomena (Bandeem and Maran, 1975) and the proceedings of the AGU International Symposium on Solar-Terrestrial Physics (Williams, et al. 1976). An excellent bibliography on this topic is provided by Shapley, et al. (1975). A symposium "Solar-Terrestrial Influences on Weather and Climate (Ohio State University-Lokcheed Palo Alto, 1978) also reviews the subject well. A recent book by Herman and Goldberg (1978) reviews extensively the correlations reported between solar activity and weather, addresses several possible physical linking mechanism, and suggests experimental concepts for further investigation.

#### Possible Solar Activity Influence on Ozone

Many of the multitude of papers written about solar activity influence on the troposphere and lower stratosphere revolve around the idea of solar activity effects on ozone. In search of a mechanism, several people have attempted to correlate atmospheric ozone content with many types of solar parameters. Willett (1963) claimed a negative correlation between the sunspot number and the worldwide average of total ozone. After inspection, however,

London and Haurwitz (1963) found that Willett's conclusion was "without statistical significance and could have arisen from a biased treatment of the data." Other correlations have been attempted, such as those carried out by Arosa and Oxford, in which their analyses also implied that changes in sunspot number followed the variations in atmospheric ozone and not vice-versa as was expected. Then a strong correlation between sunspot number and ozone concentrations at the 20 to 30 km level was cited (Paetzold, et al., 1972), while the results proved negative at altitudes greater than 30 km. Heath (1973) believes the increase in equatorial ultraviolet radiance between 2550 Å and 2900 Å, indicates a relation between the eleven-year solar cycle and the abundance of stratospheric ozone. Ruderman and Chamberlain (1975) agree that the solar cycle plays a role in the rate of ozone production and explain that it is because Nitric Oxide (a destroyer of ozone) reaches a minimum concentration during solar maximum.

The use of ozone measurements and sunspot numbers in connection with lower atmospheric temperature modes is certainly nothing new to this field. Schwentek (1971) found that the winter, but not summer, temperatures over Berlin were related to sunspot numbers. Weeks, et al. (1972) found ozone depletion in the mesosphere following the solar proton event of November 2, 1969. In his temperature model, Crutzen (1970, 1975) proposed that Nitric Oxide is produced in the polar cap in considerable quantities during solar proton events. He says that NO destroys ozone in the 30 to 45 km range, thus allowing UV radiation to sink deeper into the atmosphere, creating ozone and higher temperatures at lower levels. Ozone observations of Heath, et al. (1976) lend weight to this hypothesis. In a separate study, Ruderman and Chamberlain (1975) add to the argument by going on to say that, at higher latitudes, most changes in ozone concentrations are dependent on the ozone variations below 30 km. Zerefos and Crutzen (1975) report that at latitudes north of 50° N, long period temperatures oscillations in the 10 to 30 mb layer appear to be in phase with solar activity though the pattern does not hold south of 50° N. Schuurmans (1969), on the other hand tentatively blamed incoming solar particles for the destruction of ozone.

Solar activity effects on ozone through in-situ heating above 40 km is a rather logical mechanism to assume. The discussion above mentions hypotheses for ozone effects down to the 20 km layer. The only possible solar activity-



ozone effect on near surface weather which has been proposed involved intrusions of stratospheric air into the troposphere (Reiter, 1976).

#### Other Possible Mechanisms for Solar Activity Influence

In addition to the ozone mechanism mentioned above, several other more-or-less plausible mechanisms for solar activity influence on the lower atmosphere have been proposed: 1) cirrus cloud formation (Roberts and Olson, 1973b) from increased condensation nuclei produced by enhanced ionizing radiation during solar activity, 2) alteration of thunderstorm frequencies (and fair weather electric potential gradient) by solar activity enhanced ionization and decreased potential gradient between ionosphere and upper troposphere (Markson, 1973; Reiter, 1976b). An inverse relation between cosmic ray flux and solar activity is well established (Forbush, 1957), 3) enhancement of polar region vorticity and direct viscous coupling between ionosphere and troposphere (Hines, 1973), 4) alteration of tropospheric angular momentum by modification of planetary wave reflection at higher altitudes (Hines, 1973, 1974; Hines and Halevy, 1975, 1977). This mechanism would only be operative during winter months when wind patterns allow planetary wave propagation to ionospheric heights where reflection may occur. The observed phase relations of planetary scale oscillations between stratosphere and ionosphere by Ebel, et al. (1976) would tend to support this hypothesis. However, the study of gravity waves and traveling planetary waves by the daily difference method of Justus and Woodrum (1973) showed no difference in wave magnitudes during solar activity days.

#### Possible Influence of Solar Activity on the Middle Atmosphere

Compared to the large body of material on the solar activity effects on the upper atmosphere ( $\geq 90$  km) and possible solar influence of solar activity on the lower atmosphere ( $\leq 20$  km), relatively little work has been done on the middle atmospheric region (mesosphere and upper stratosphere). Only a few correlations have been attempted, because of the shortcomings of middle atmospheric data. The majority of the papers on this region seem to deal with the ionization of constituents through the absorption of various wavelengths of solar radiation. Reid (1970), Ackerman (1971), Krueger (1969), and Thomas and Bowman (1969) collectively investigated the effects on molecular

oxygen due to radiation between  $1 \text{ \AA} - 6000 \text{ \AA}$ . Electron density in the 30-65 km layer is discussed by Reid (1970) and Potemra and Zmuda (1970). The precipitation of particles during solar proton events is thought to drastically reduce mesospheric ozone. Ramakrishna (1971) and Ramakrishna and Seshamani (1973) have noted a correlation between solar EUV emissions and equatorial mesospheric temperature variations. More recently (Seshamani and Ramakrishna, 1978) they have noted heating effects in the equatorial mesosphere following sector boundary crossings which they relate to energetic particle flux variations within the sector structure. Kazimirovskii and Longinov (1973) found solar activity ( $F_{10.7}$  and  $A_p$ ) effects on the high latitude upper stratospheric zonal wind. Nastrom and Belmont (1976) found relationships between the 30-65 km temperature and annual and semiannual zonal winds and the geomagnetic field elements, but found no temperature and solar sector structure correlation. Ebel and Batz (1977) have found a relationship between 10 mb (30 km) surface heights and solar activity changes due to the rotation of the sun (27 day period).

A feasible mechanism for middle atmosphere solar activity influence, involving not only temperature, but density, pressure, and circulation as well, would indeed seem to lie in the complex absorption processes of this region. A better understanding of UV, X-ray, and cosmic radiation behavior of the mesosphere and upper stratosphere may not only lead us to a plausible working model of solar activity influence on the middle atmosphere, but may also prove to be the link between the upper and lower atmosphere through one (or more) of the mechanisms discussed above.



## 2. DATA SOURCES AND ANALYSIS METHODS

This study examines the possible solar activity influence on the upper stratosphere and mesosphere (25-90 km). Various hypotheses for direct middle atmosphere influence have been examined. Several different meteorological parameters of the middle atmosphere were investigated in connection with several different solar activity indicator parameters. Some analyses were done by "superposed epoch" analysis (where only timing factors are examined), and other analyses were done by cross-correlation or linear regression analyses (where both timing and magnitudes of both solar activity and meteorological phenomena are to be studied).

The following sub-sections give details of the solar activity parameters studied, the meteorological parameters examined jointly with the solar activity parameters, and the methods of analysis used.

### Solar Activity Parameters Analyzed

- AE Index - The AE index, taken at 2.5 minute or hourly intervals, is a measure of auroral electrojet activity. It describes the instantaneous range of disturbance of the horizontal component, H, from latitude aligned observatories ( $19^\circ$  to  $30^\circ$  colatitude).  $AE = \Delta H(\max) + |\Delta H(\min)|$ , where  $H(\max)$  represents the maximum positive deviation of H, and  $|\Delta H(\min)|$  is from the largest negative value of H. The AE index has not been used extensively in solar activity studies. Continuous data were obtained for the AE index for the year 1966 through 1974. A plot of daily average AE index values is given in Figure 1.
- $D^{st}$  Index - The  $D^{st}$  index is calculated at both 2.5 minute and hourly intervals. It is defined as the "component of the disturbed magnetic field axially symmetric with respect to the geomagnetic dipole axis."  $D^{st} = 1/n(\Delta H_1 + \Delta H_2 + \dots \Delta H_n)$ . It is therefore a measure of equatorial magnetic activity due to the ring current. These measurements are also made by observatories in low magnetic co-latitudes ( $<35^\circ$ ).  $D^{st}$  is defined in such a way that values are lower (more negative) for higher magnetic activity. Continuous data for  $D^{st}$  were obtained for

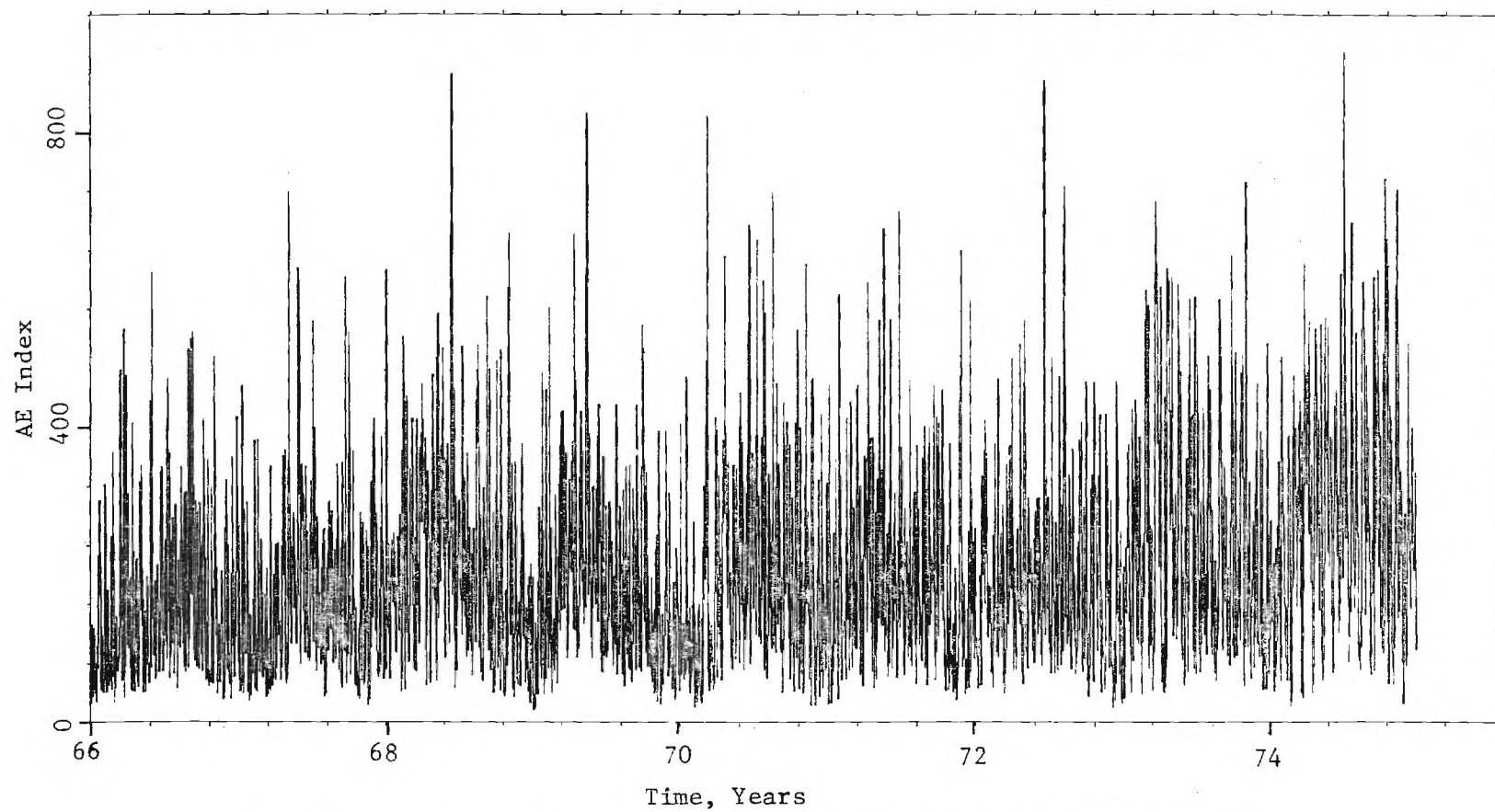


Figure 1. Daily Average AE Index Versus Time for 1966 Through 1974.

the years 1964 through 1975. Daily average values of  $D^{st}$  are plotted in Figure 2. The  $D^{st}$  index has, like the AE index, not been used extensively in solar activity studies.

$F_{10.7}$  - The  $F_{10.7}$  cm flux is a measure of solar radio noise. This index has been used extensively in attempts to show relationships between solar activity and atmospheric parameters. Its significance is primarily as an indicator of solar EUV flux, with which it is correlated. Continuous data on  $F_{10.7}$  were obtained for 1964 through 1976. Daily averages of  $F_{10.7}$  are plotted in Figure 3.

Sunspot No. - The Zurich sunspot number,  $R$ , an index often used in solar activity studies, is defined as  $R = k(10g + f)$ , where  $f$  is the total number of spots, regardless of size,  $g$  is the number of spot groups, and  $k$  normalizes the counts for different observatories. Figure 4 gives a plot of the daily sunspot number versus time for 1964 through 1976.

Solar Wind - As measures of the solar wind intensity and its effects on the interplanetary magnetic field, daily averages of solar wind temperature, density, speed, and magnetic field strength were used. These data were obtained from National Space Sciences Data Center (NSSDC) "OMNI" tapes. The OMNI tapes contain magnetic field and solar wind parameters measured by Explorer series satellites, HEOS, VELA, and OGO. Figures 5 and 6 show plots of the daily average solar wind particle density and magnetic field strength for the years 1965 through 1975.

Cosmic Rays - Cosmic ray data in the form of daily average neutron count rate from three ground stations were obtained through World Data Center A. The three stations used were Sulfur Mountain (latitude  $51^\circ$  N, longitude  $115^\circ$  W, cut-off rigidity 1.14), Deep River ( $46^\circ$  N,  $77^\circ$  W, cut-off rigidity 1.02), and Alert ( $82^\circ$  N,  $62^\circ$  W, cut-off rigidity 0.00). The data used were barometrically corrected count rates, to remove influences of variations in the physical mass of air above the observing stations. Figure 7 gives a plot of daily cosmic ray neutron count rate from the Alert station for 1965 through 1974. Minimum count

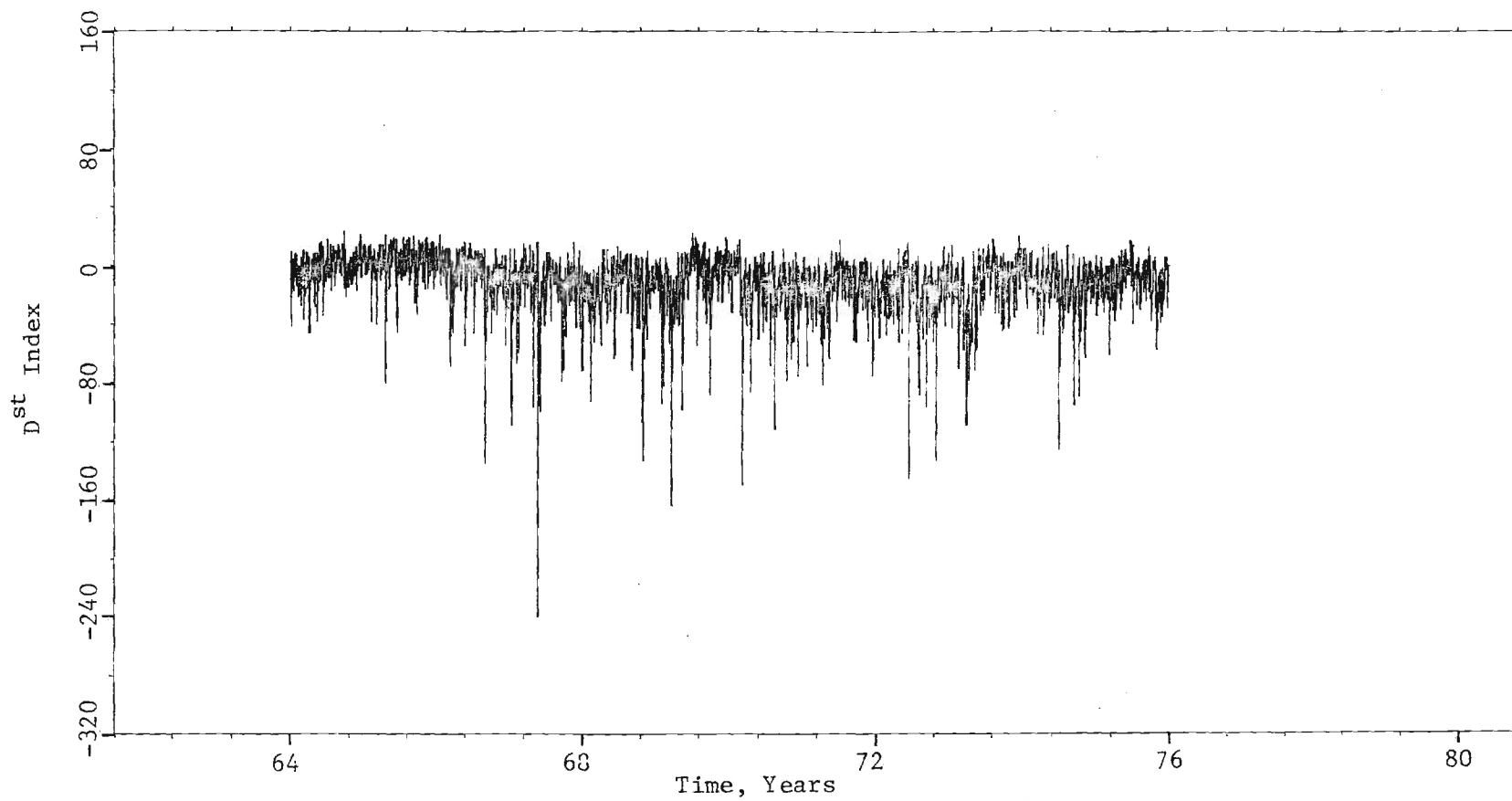


Figure 2. Daily Average D<sup>st</sup> Index Versus Time for 1964 Through 1975.

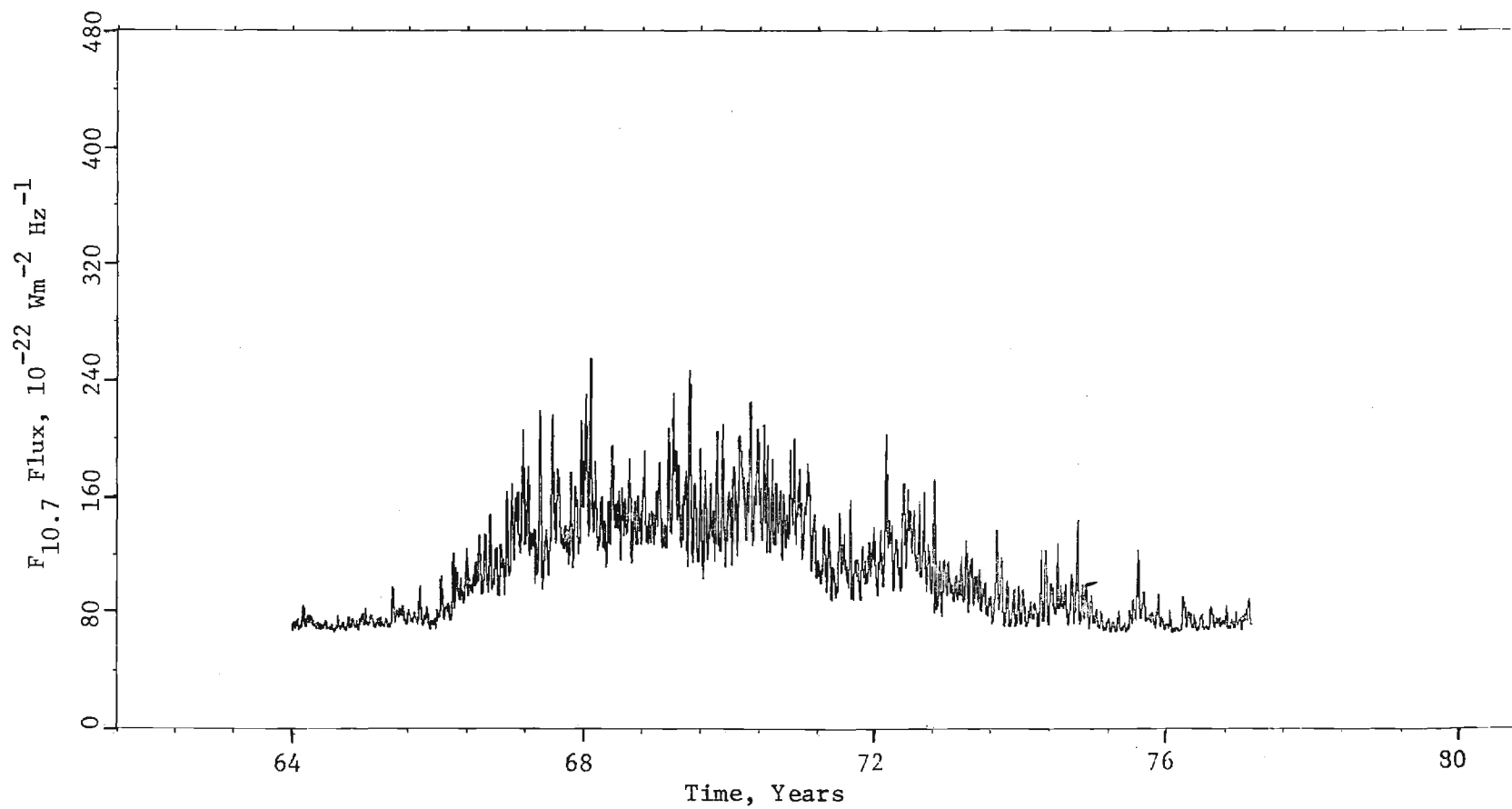


Figure 3. Daily Average 10.7 cm Solar Flux ( $F_{10.7}$ ) Versus Time for 1964 Through 1976.

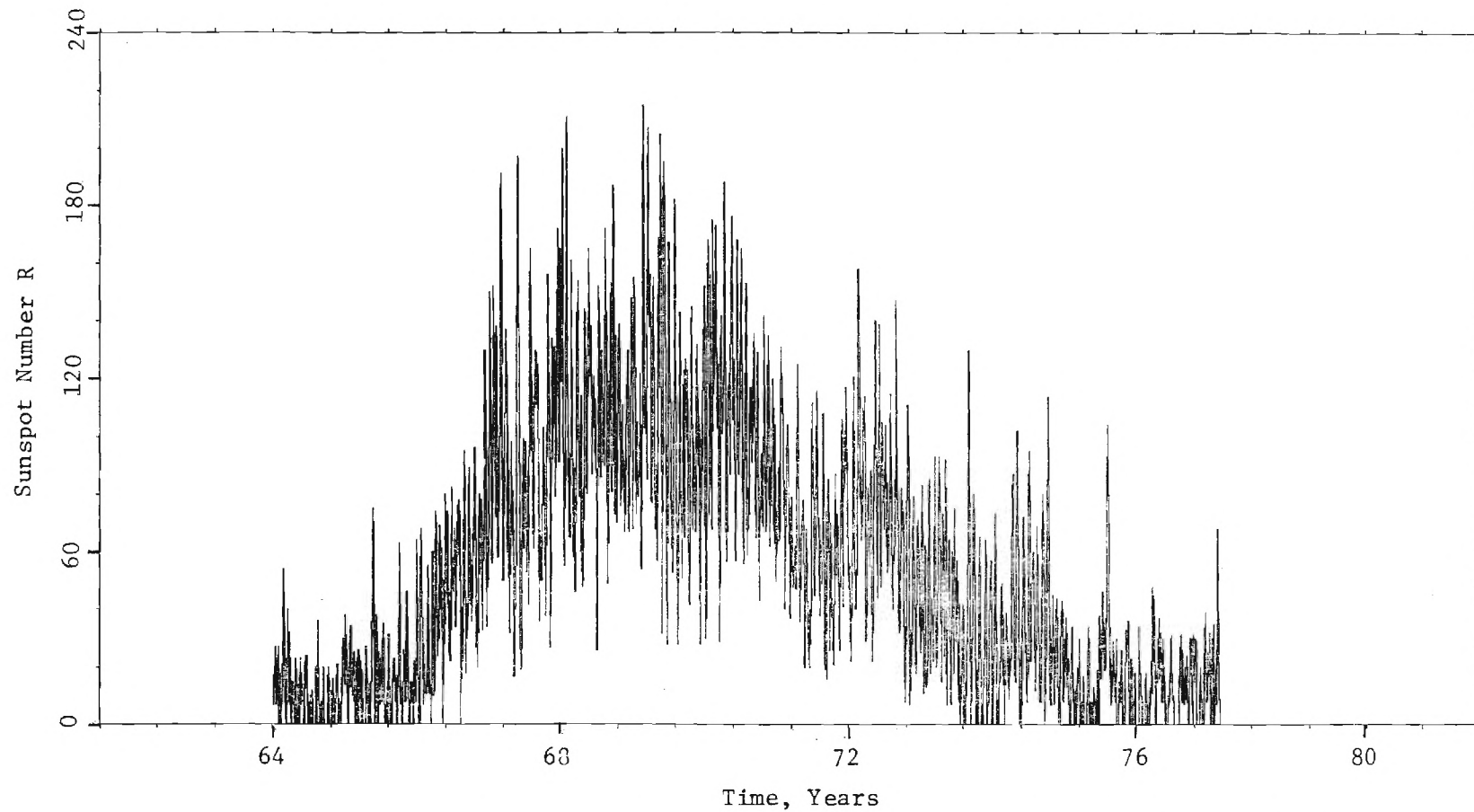


Figure 4. Daily Average Sunspot Number Versus Time for 1964 Through 1976.

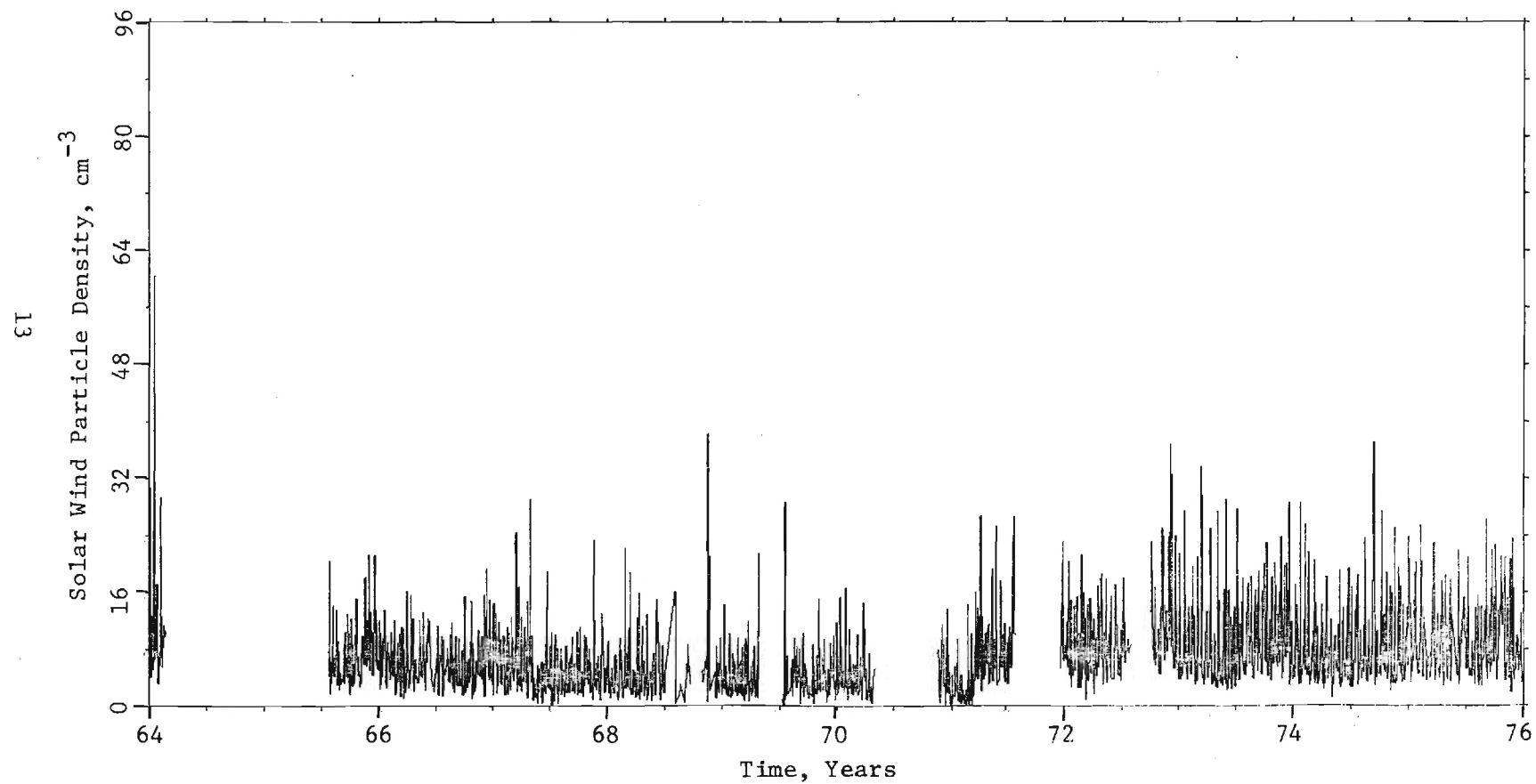


Figure 5. Daily Average Solar Wind Particle Density Versus Time for 1965 Through 1975.

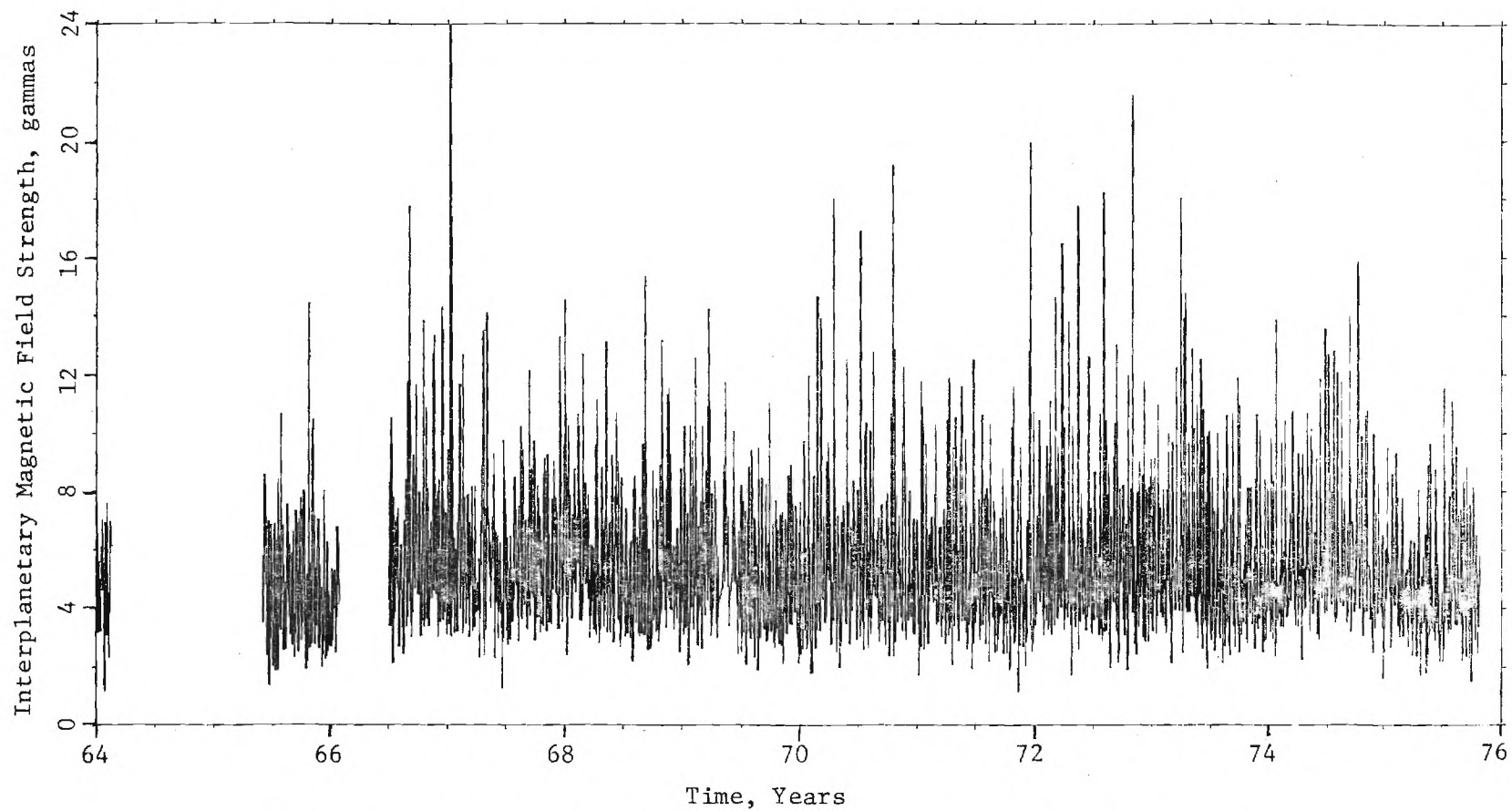


Figure 6. Daily Average Interplanetary Magnetic Field Strength Versus Time for 1965 Through 1975.



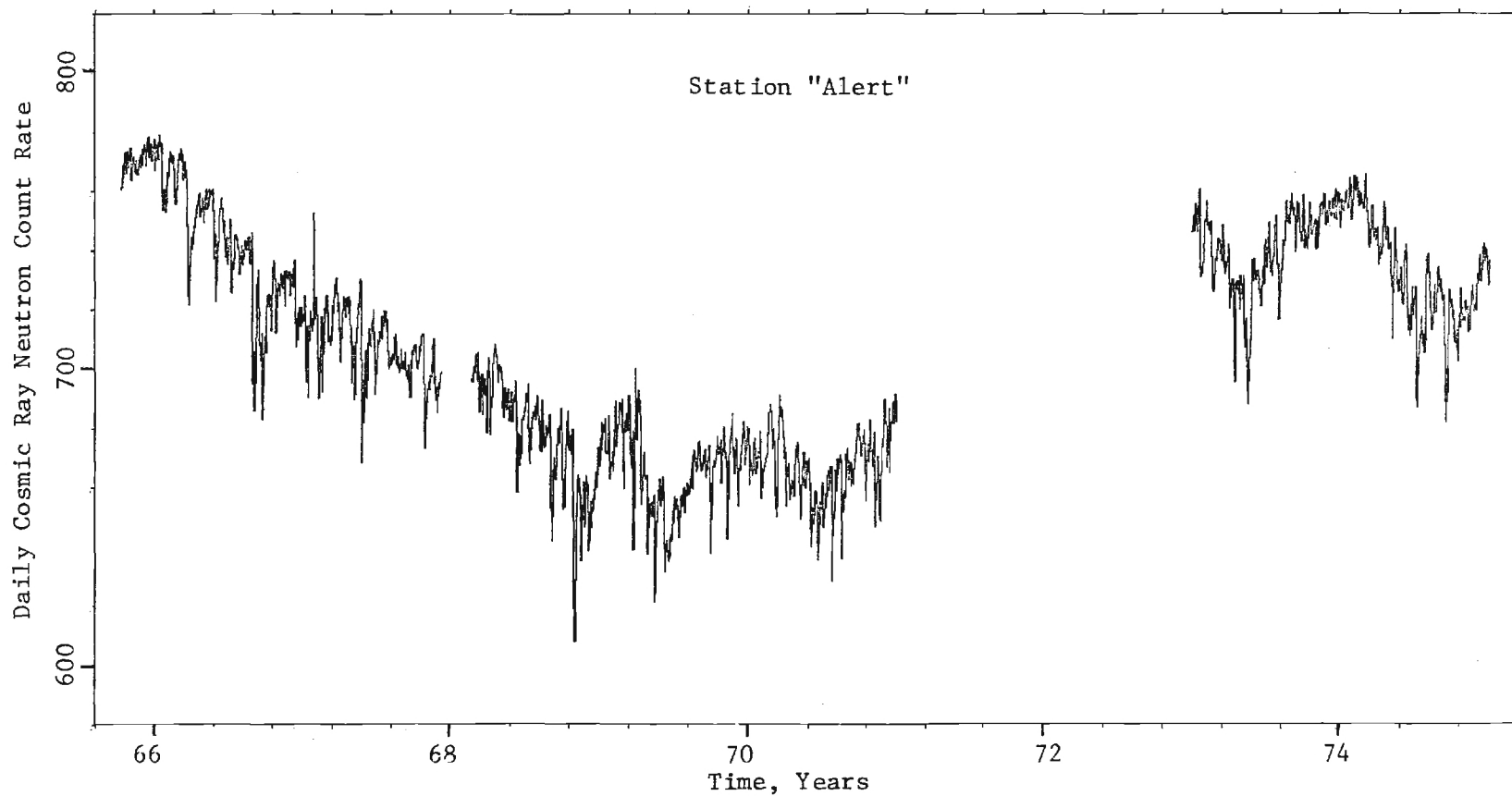


Figure 7. Daily Total Cosmic Ray Neutron Count at Alert Station (82° N, 62 °W) for 1965 Through 1974.

rates in the 1968-1970 period correspond to maximum solar activity (e.g., peak sunspot number or peak  $F_{10.7}$  in Figures 3 or 4) because of the Forbush decrease effect (Forbush, 1957).

**Solar Proton Flux** - Hourly average solar proton flux data were obtained on magnetic tape through NSSDC. These data were 60 Mev, 30 Mev, 10 Mev, and 1-10 Mev proton flux rates as measured by IMP series (primarily IMP F and IMP G) satellites. Daily averages were constructed for the 60 Mev and 1-10 Mev proton flux data for 1969 through 1972. These data are characterized by large variations between more-or-less quiescent periods and high count rates during proton flare periods - the most notable of which was the August 1972 solar proton event.

**Solar Sector Boundary** - A solar sector boundary is the line of demarcation between the zones of outward and inward solar magnetic field. These have been measured both by satellite and interplanetary probe and from ground based polar magnetometers, [although magnetometer inferred sector boundaries are somewhat suspect (Fougere, 1974)]. Times of solar sector boundary crossings at the earth, as tabulated by Svalgaard (1976) were used for the period 1964 through 1975. All of these data are from the period when satellite observations were used to infer sector structure. Hence, these data do not have the potential problem pointed out by Fougere. Solar sector passages and solar flares were used as establishing "key days" in superposed epoch studies.

**Solar Flares** - Solar flares are short-lived increases in  $H\alpha$  emission which occur usually in a solar region encompassed by a large, magnetically bipolar sunspot group. Flares last from a few minutes to a few hours, and are usually accompanied by an enhancement in X-ray emission. Prior to 1966, flares were characterized by a scale running from 1- to 3+ according to their intensity. After 1966, an international scale was used of 1 to 4 followed by a letter F (faint), N (normal), or B (brilliant). The occurrence of flares, especially those of lower intensity, is correlated with the 11 year solar cycle. However, major flares can occur at any time during the cycle. For purposes of

this study, a list of flares defined by the Comprehensive Flare Index (Dodson and Hedeman, 1971, 1975) were used. Their index is based on the ionizing radiation importance (1-3), the H $\alpha$  importance (1-3), the magnitudes of the 10 cm flux and 200 MHz flux, and the dynamic spectrum (Type II = 1, Continuous = 2, and Type IV = 3) for the flare. Flares selected for establishing "key days" for superposed epoch studies were those classified as 9 or higher in the Comprehensive Flare Index Scheme. Table 1 gives a summary of occurrence of these flares by month and year for the study period. The correlation with solar cycle, as characterized by sunspot number or 10.7 cm flux in Figures 3 or 4, is evident in Table 1.

Other Solar - X-ray and EUV flux data were obtained on magnetic tape from Data NSSDC for Solrad 7A, 8, and 9, OSO 2, 3, and 5, Explorer 35 and Vela 5A. Cosmic Ray data outside earth's atmosphere were available from OGO 1, OGO 3, and HEOS 1 from 1964 through 1971. However, these data proved to be unusable in this study because of several time gaps in the data.

#### Stratosphere-Mesosphere Meteorological Data Studied

Meteorological Rocket Network (MRN) data from the NOAA National Climatic Center, for MRN sites Thule, Ft. Greely, Ft. Churchill, Wallops, Mugu, White Sands, Kennedy, Barking Sands, and Ascension for the years 1964 through 1974 were used as a source of temperature, density, and wind data for the 25-65 km altitude range. These were supplemented by grenade and pitot tube data (Smith, et al., 1964-74) for the altitude range up to about 90 km. Meteorological parameters read from data tapes for these sites included temperature, density, and pressure departures from climatological monthly mean ( $T - \bar{T}$ ), ( $\rho - \bar{\rho}$ ) and ( $p - \bar{p}$ ), and zonal and meridional wind component departures from climatological mean ( $u - \bar{u}$ ), and ( $v - \bar{v}$ ). The MRN monthly means were evaluated from the National Climatic Center "SUMS Tape" average data. The grenade data climatological averages were taken from Theon, et al. (1972).

Daily difference analysis of the MRN data was used to determine magnitudes of gravity waves and planetary waves in the 25-65 km height range (Justus and Woodrum, 1973), especially for use in examining the Hines wave

Table 1. Summary of Occurrence of Solar Flares with Comprehensive Flare Index Greater than 9.

Year	Comprehensive Flare Index									Total
	9	10	11	12	13	14	15	16	17	
1964	-	-	1	-	-	-	-	-	-	1
1965	1	-	-	-	-	-	-	-	-	1
1966	2	6	2	3	2	2	-	1	-	18
1967	8	1	-	6	-	-	-	1	-	16
1968	17	6	1	2	1	2	-	-	1	30
1969	5	5	2	9	2	4	-	-	-	27
1970	10	10	10	4	4	4	-	-	-	42
1971	5	4	2	1	1	-	-	-	-	13
1972	4	5	6	1	3	1	1	1	-	22
1973	4	3	3	1	1	-	2	-	-	14
1974	4	4	3	5	1	4	-	-	-	21
Totals	60	44	30	32	15	17	3	3	1	205

interference hypothesis of solar activity influence (Hines, 1973, 1974; Hines and Halevy, 1975, 1977). Details of the analyses of these MRN data are given in the following section.

The other basic forms of meteorological data employed were hemispheric average thickness values between 5 and 0.4 mb surfaces and circulation index values for the 5 and 0.4 mb levels. These data were taken from the 5 and 0.4 mb upper air charts prepared for 1964 through 1973 by NOAA (1967-1975). The 5 to 0.4 mb thickness study complements well the earlier studies [e.g., Zerefos and Crutzen (1975), Ebel and Betz (1976)] which looked at heights and thicknesses up to the 10 mb level.

Thickness values, which are proportional to the mean temperature for the layer, were evaluated by differencing height values read from individual upper air maps (generally prepared on a weekly time schedule). Thickness values were thus determined around a 30° N and 70° N latitude circle. These values were then averaged to yield the hemispheric mean thickness between 5 mb and 0.4 mb levels.

The height values around the 30° N and 70° N latitude circles were also used to determine hemispheric circulation index values for each level. The circulation is defined as the zonal mean difference between 70° N and 30° N height values (defined in such a way that this index is positive for cyclonic mean circulation around the pole). By the geostrophic wind relations, the circulation index defined in this manner is proportional to the zonal mean of the averaged geostrophic wind across the 30° N to 70° N section.

Figures 8-10 show plots of the weekly average 5-0.4 mb thickness and the circulation index at 5 mb and 0.4 mb. Note the smooth variations of circulation and thickness values during the summer months and the rapid fluctuations in winter seasons. Circulation reversals or near-reversals in winter are associated with stratospheric warming events.

#### Analysis Methods Used

Two analysis methods were used in this study: correlation analysis and superposed epoch analysis. For the MRN data, the parameters studied were the daily difference values representing perturbations from the mean atmosphere (0-day differences), gravity wave magnitudes (1-day differences), or large scale traveling planetary wave magnitudes (7-15 day differences). The

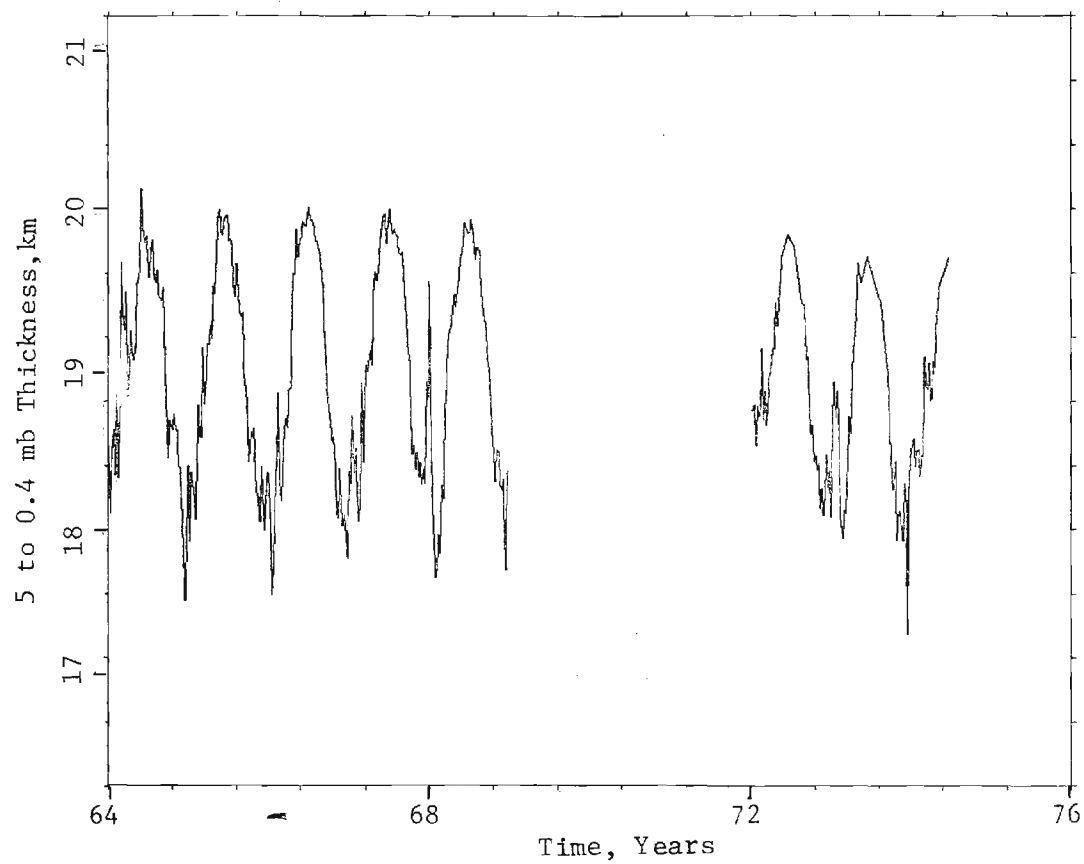


Figure 8. Weekly Average Thickness Values for 5-to-0.4 mb Layer for 1964 Through 1974.

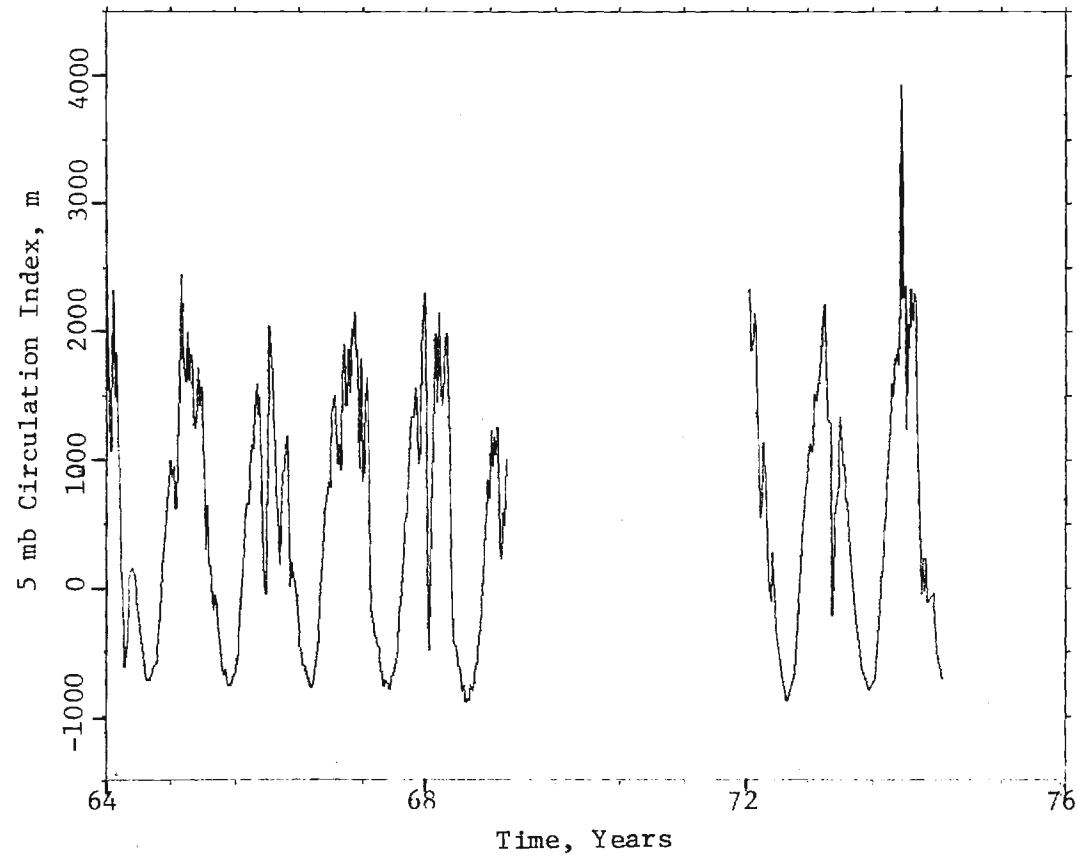


Figure 9. Weekly Average Zonal Circulation Index for the 5 mb Level 1968 Through 1974.

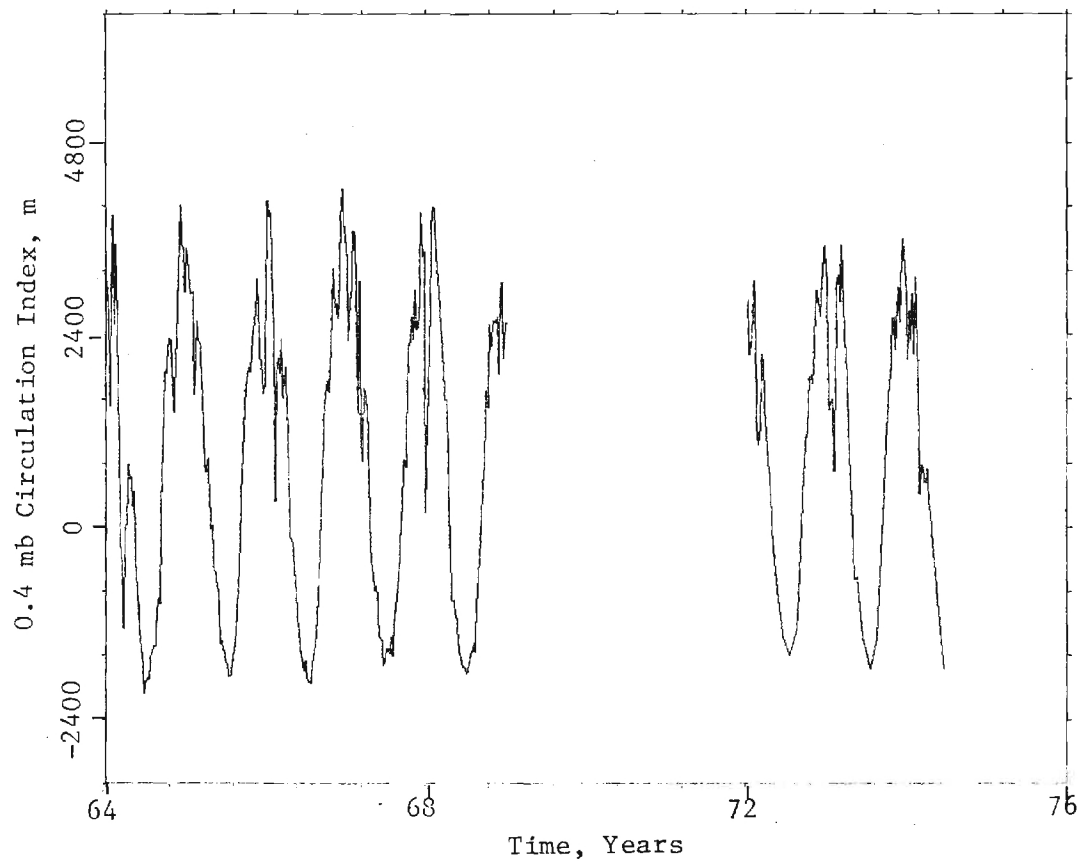


Figure 10. Weekly Average Zonal Circulation Index for the 0.4 mb Level 1964 Through 1974.



following discussion describes the analysis of daily differences and justifies the argument for associating these wave magnitudes with the daily difference magnitude values.

Daily difference analysis makes use of structure functions. The structure function is an alternate form of the correlation function first used extensively by Russian meteorologists in the analysis of turbulence. The structure function of a statistically stationary time varying process  $f(t)$  is given by

$$D(\tau) = \langle [f(t + \tau) - f(t)]^2 \rangle, \quad (1)$$

where the structure function  $D$  depends only on the time displacement  $\tau$  because of the statistical stationarity. The angle brackets in (1) denote averaging.

The daily difference analysis technique was developed (Justus and Woodrum, 1972, 1973) for applications where limited data did not allow explicit separation of the tidal components in order to determine the small scale irregular variations. As an example of the application of this technique, consider a vertical profile of a parameter  $F(z, t)$  over height  $z$  at time  $t$  where  $F$  may be a wind component, pressure, density, or temperature. We consider that  $F$  is made up of a prevailing value  $F_0(z)$  which is time invariant, plus a long period (e.g., a standing wave or a seasonal, annual, or quasi-biennial oscillation) component  $S(z, t)$ , a planetary scale or synoptically varying component  $P(z, t)$ , a tidal component  $T(z, t)$ , a gravity wave or short period irregular component  $G(z, t)$ , and a still smaller scale component made up of measurement error and turbulence  $E(z, t)$ . Thus

$$\begin{aligned} F(z, t) = & F_0(z) + S(z, t) + P(z, t) + T(z, t) \\ & + G(z, t) + E(z, t) \end{aligned} \quad (2)$$

The component  $P(z, t)$  would be composed of traveling waves only, all truly standing waves would be included in the component  $F_0(z)$  or seasonally fluctuating standing waves would be included in  $S(z, t)$ . We now choose two profiles of  $F$  at times  $t_1$  and  $t_2$  such that  $t_2 - t_1 = \Delta t = 24n$  hours where  $n$  is an integer. If, at any selected altitude  $z$ , we difference the corresponding values of  $F$  then

$$\begin{aligned}
F_n(z) = F(z, t_2) - F(z, t_1) = & [S(z, t_2) - S(z, t_1)] \\
& + [P(z, t_2) - P(z, t_1)] + [T(z, t_2) - T(z, t_1)] \\
& + [G(z, t_2) - G(z, t_1)] + [E(z, t_2) - E(z, t_1)] \quad (3)
\end{aligned}$$

We now make the assumptions: (1) Assume that  $n$  is sufficiently small that  $S(z, t_2) \approx S(z, t_1)$  (i.e.,  $n$  is a small number of days compared to times over which appreciable seasonal variation would occur). In the analysis, we restricted  $n$  to 15 or less days. (2) Assume that because the tidal component is diurnally repeating and  $\Delta t$  is a multiple of 24 hours that  $T(z, t_2) = T(z, t_1)$ . (Any systematic or synoptic variation in the tidal parameters would be included in the component  $P$  and the seasonal variation of the tides would be included in the component  $S$ ). (3) The planetary scale, gravity wave and error components are uncorrelated with each other and are correlated only with themselves (autocorrelation). Equation (3) can now be squared and averaged over an ensemble of different profile pairs all having the same time separation  $\Delta t$ . The result is

$$\begin{aligned}
\langle [\Delta F_n(z)]^2 \rangle = & \langle [P(z, t_2) - P(z, t_1)]^2 \rangle \\
& + \langle [G(z, t_2) - G(z, t_1)]^2 \rangle + \langle [E(z, t_2) - E(z, t_1)]^2 \rangle \quad (4)
\end{aligned}$$

The cross product terms in (4) have dropped out because of assumption 3 above. If equation (4) is now expanded and the mean square values of  $P$ ,  $G$ , and  $E$  are assumed to be independent of time (i.e., statistically stationary) then the mean square data differences become

$$\begin{aligned}
\langle [\Delta F_n(z)]^2 \rangle = & 2\langle P^2(z) \rangle [1 - \rho_P(\Delta t)] \\
& + 2\langle G^2(z) \rangle [1 - \rho_G(\Delta t)] + 2\langle E^2(z) \rangle [1 - \rho_E(\Delta t)] \quad (5)
\end{aligned}$$

where  $\rho_P$ ,  $\rho_G$ , and  $\rho_E$  are the time autocorrelation functions of  $P$ ,  $G$ , and  $E$  respectively. The following assumptions are now made about the periods of the various remaining components: (1) the gravity wave, error and turbulence

components are uncorrelated for all time differences of 1 day or more (i.e.,  $n \geq 1$ ), (2) the planetary wave component is of such a long period that  $\rho_p(\Delta t) \approx 1$  for  $\Delta t = 1$  day, but for large  $n$  the planetary wave component also becomes uncorrelated. Thus for single day differences, equation (5) becomes

$$\langle [\Delta F_1(z)]^2 \rangle = 2[\langle G^2(z) \rangle + \langle E^2(z) \rangle] \quad (6)$$

that is, the mean square differences in the observed data are equal to twice the mean square magnitude of the gravity wave component (plus any contribution from measurement errors or small scale turbulence). For time separations of many days ( $n$  large, say approaching 15) and under the above assumptions equation (5) becomes

$$\langle [\Delta F_n(z)]^2 \rangle = 2[\langle P^2(z) \rangle + \langle G^2(z) \rangle + \langle E^2(z) \rangle] \quad (7)$$

thus, at longer time separations, the magnitude of the planetary wave contributions becomes added. At intermediate time separations progressively larger portions of the planetary wave contribution [through the factor  $1 - \rho_p(\Delta t)$ ] become added. Equations (6) and (7) can be subtracted, which yields

$$\langle [\Delta F_n(z)]^2 \rangle - \langle [\Delta F_1(z)]^2 \rangle = 2\langle P^2(z) \rangle \quad (8)$$

This allows an estimate of the contribution of planetary waves directly from the observed daily differences of measured data and the estimate is unbiased with respect to the error component  $\langle E^2 \rangle$  since that component cancels in the subtraction process. Note, however, that this method, like any single site method, does not resolve the standing planetary wave components, only the traveling components.

The assumptions outlined above regarding relative periods of the gravity wave and planetary wave components (and the implicit assumption that the errors are sufficiently small that meaningful results can be obtained from the analysis) are subject to verification. The results presented by Justus and Woodrum (1972, 1973) confirm these assumptions.

For this particular study, the height range of the data was divided into three zones 25-45 km, 45-65 km (MRN data), and above 65 km (Grenade data).

In each zone, the rms difference between the profile value and the climatological mean (from the SUMS tape) was evaluated and called the 0-day difference value for that profile. If a profile was available 1 day later, the rms differences between these two profiles over the height range considered was evaluated and called the 1-day difference. For all profiles within the range of 7-15 days later, the profile pairs were similarly differenced and rms averaged and called the 7-15 day difference for the original profile. Five meteorological parameters--pressure, density, temperature, zonal wind, and meridional wind--were analyzed in this manner for the three height ranges for the several sites considered. After this analysis was completed, it was determined that too few data, especially of the 1-day difference type, were available for the above 65 km height range and that sufficient data were available in the 25-45 km and 45-65 km ranges for only three MRN sites: Ascension Island (8° S, 140° W), Kennedy SFC (28° N, 80° W), and Ft. Churchill Canada (50° N, 94° W).

Figure 11 illustrates the 0-day differences for zonal wind component for Ft. Churchill in the 25-45 km height range (rms averaging interval). Note the smooth variations in summer and rapid fluctuations in winter.

Each meteorological parameter (0-day, 1-day, or 7-15 day differences in temperature, density, pressure, or wind component; hemispheric 5 mb circulation, 0.4 mb circulation and 5 mb - 0.4 mb thickness) was cross-correlated with each of the solar activity parameters, either in a correlation analysis, or with a "superposed epoch" analysis. The superposed epoch analysis is useful when there is only timing information used about the solar related phenomena (e.g., time of solar sector boundary crossing). In that case, the solar parameter time serves as the "key" on which the meteorological parameter magnitudes before and after the key time can be compared for evidence of influence. For solar parameters with both magnitude and time (e.g., solar wind density  $X(t)$  versus time  $t$ ), a cross-correlation with meteorological parameter (say,  $Y(t)$ ) can be done by evaluating the cross-correlation  $R(\Delta t)$ .

$$R(\Delta\tau) = \langle [X(t) - \bar{X}][Y(t + \tau) - \bar{Y}] \rangle / (\sigma_X \sigma_Y) \quad (9)$$

where the angle brackets denote averaging over the data set and  $\sigma_X$  and  $\sigma_Y$  are

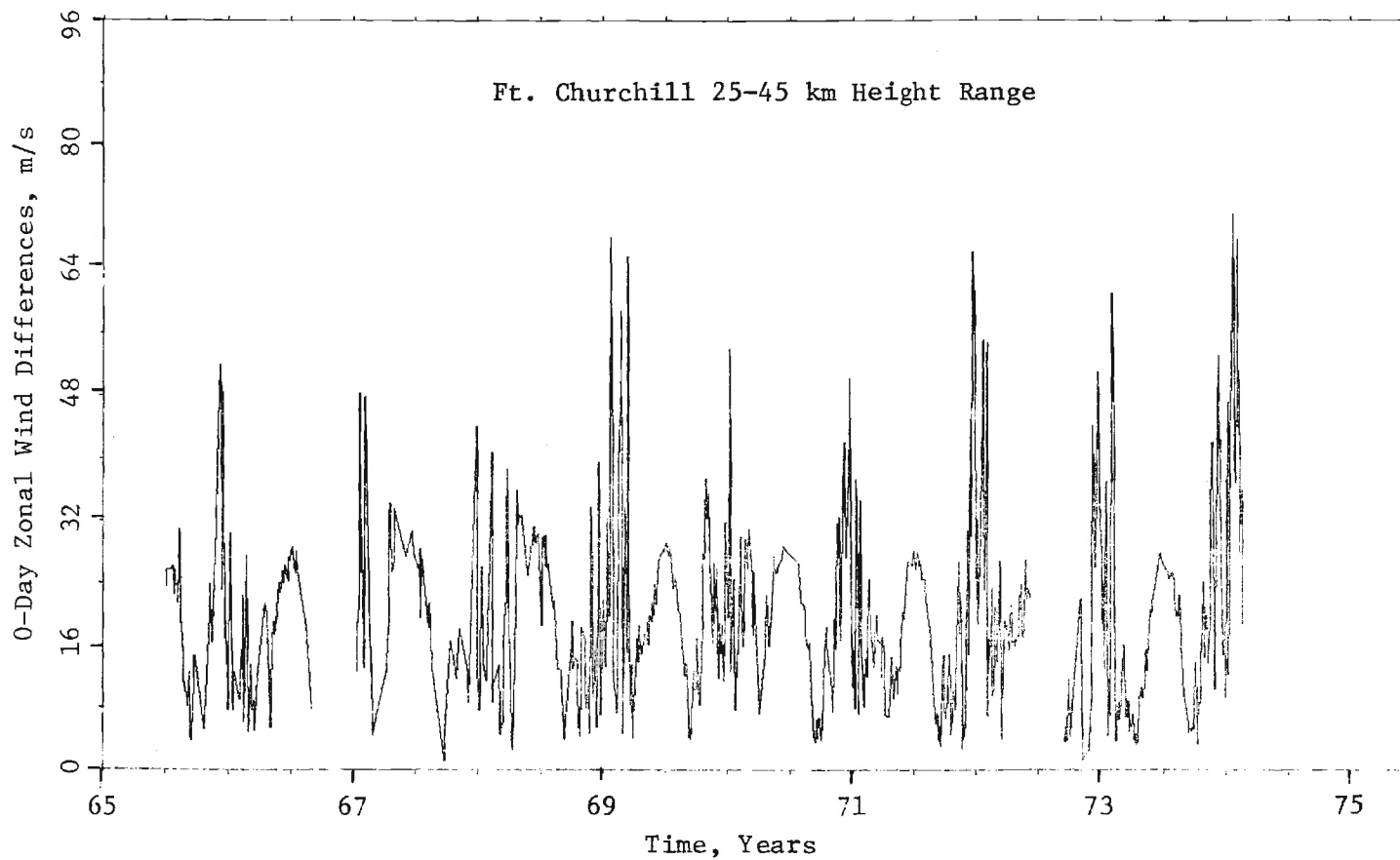


Figure 11. 0-Day Differences in Zonal Wind Component for the 25-45 km Height Range for Ft. Churchill 1965 Through 1974.

the standard deviations. For each type of analysis, confidence intervals were evaluated to examine level of significance of the results.

The superposed epoch analysis method can be used for parameters, such as solar sector boundary crossings or flare occurrences, for which only timing (not magnitude) information is available. The events (e.g., boundary crossings or flares) serve to establish a set of "key days," and rms averages of the meteorological parameter to be compared are then averaged as a function of number of days before or after one of the key days in the set. Standard deviations are also evaluated so that changes in averages-versus-key days can be compared against the standard deviations to determine the level of significance of these changes in the average values.

For other parameters which are specified as magnitude versus time (sunspot number,  $F_{10.7}$ , solar wind density, interplanetary magnetic field strength, etc.) the superposed epoch analysis can also be done. In such cases, the set of key days is defined by those days on which the magnitude of the parameter under investigation first exceeds a pre-selected threshold value. Following each key day defined in this manner, the parameter in question may remain above the threshold value for some number of subsequent days. However, the next key day is defined as that day after the parameter has returned below the threshold when it once again exceeds the threshold value. By these definitions, neither the length of continuous time spent above the threshold nor the maximum value attained has any effect on the selection of key days for the superposed epoch analysis.



### 3. CORRELATION ANALYSES AND RESULTS

#### The Parameter Combinations Studied

Many studies have been done which look at one or two meteorological variables and one or two solar activity indices and use only correlation analysis or only superposed epoch analysis. With different studies using different data and different techniques, comparison of results and implications regarding their significance are difficult to make. The completeness of the current study, with regard to the meteorological parameters of the 25-65 km height range and the large list of solar indices examined allows for better interpretation of the results.

The number of combinations of solar parameters and atmospheric parameters available for correlation or key day analysis in this study is quite large. The meteorological data base, as described in the previous section, consists of 90 daily difference parameters: 5 variables (pressure, density, temperature, zonal wind, meridional wind) times 3 daily difference types (0-day differences, 1-day differences, or 7-15 day differences) times 3 sites (Churchill, Kennedy, or Ascension) times 2 height ranges (25-45 km or 45-65 km). Also included are 3 hemispheric meteorological parameters (5-0.4 mb thickness, 5 mb circulation index, and 0.4 mb circulation index), for a total of 93 meteorological parameters. There were 13 solar activity parameters which could be used in both correlation and superposed epoch analyses (interplanetary field strength; solar wind density; solar wind temperature; solar wind speed; 1-10 Mev proton flux; 60 Mev proton flux; AE index;  $D^{st}$  index; cosmic ray neutron flux at Sulfur Mountain, Deep River, and Alert; sunspot number; and 10.7 cm flux index F10.7) as well as 2 solar activity parameters suitable only for superposed epoch analysis (flare dates and solar sector boundary crossing dates). These lead to a possible 2604 combinations of meteorological and solar parameter (93 meteorological times 13 solar for correlation, plus 93 meteorological times 15 solar for superposed epoch). If seasonal as well as annual analyses were to be done, this would lead to over 13,000 possible relationships to evaluate (2604 parameter pairs times 5 season or annual). Obviously, this total of possible calculations had to be reduced to keep it within a manageable size. It was decided that only summer and winter seasonal daily difference correlations would be done,

since these seemed the likely seasons in which significant correlations, if any, would show up. Only annual (i.e., all four seasons combined) superposed epoch studies were done for the daily differences, however. Proton flux data were used only in superposed epoch mode, because of the increase by orders of magnitude in the flux during flare type events. For thickness and circulation data, 13 solar parameters were correlated with all three hemispheric meteorological parameters for the four seasons, as well as annual. Superposed epoch analysis was done on thickness only and only for flares, with all seasons combined. This selection of parameter combinations still resulted in over 3500 meteorological parameter-solar parameter combinations.

#### Daily Difference Correlation Results

For each combination of meteorological and solar parameter studied, the cross-correlation function was evaluated for lags from -6 to +10 days (i.e., meteorological parameters 6 days earlier to 10 days later than the solar parameter). Figure 12 gives an example of the correlation function results versus lag for one such parameter combination. For each correlation function versus lag, the most significant correlation value was selected (based on a t-test with the standard deviation of the correlation values). Tables 2-4 (winter) and Table 5 (summer) present the results for these most significant correlations. These tables show the correlations which exceeded 0.3 in magnitude and which were better than 1% significance level in a t-test based on value and estimated standard deviation in the correlation. Blanks in Tables 2-5 indicate correlations less than or equal to 0.3 in magnitude or significance levels of worse than 1%. The X's in Tables 2-5 indicate insufficient data for a meaningful t-test (numbers in the correlation of less than 20).

Table 5 gives only selected solar parameters for the three daily difference sites for the summer season (June, July, August), whereas the full set of solar parameters correlated is shown in Tables 2-4 for the winter season (December, January, February).

#### Superposed Epoch (Key Day) Results

Flares and solar sector boundary crossings form natural "key days" for superposed epoch analysis. For these cases, the mean values of the meteorological parameters (the vertical rms daily differences of rocket data profiles)



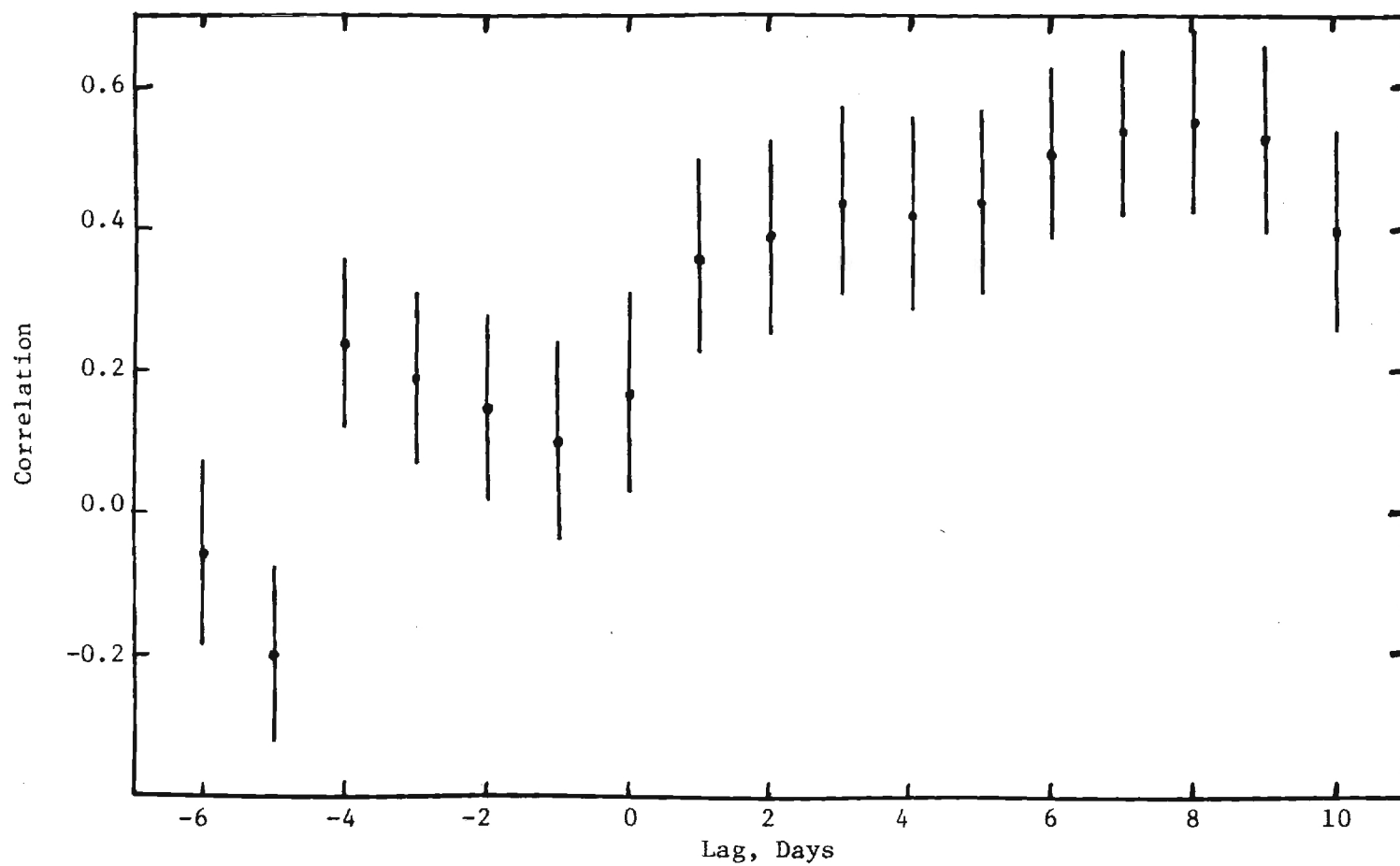


Figure 12. Winter Seasonal Correlation of 1-Day Daily Differences in Zonal Wind at Ascension with Alert Station Cosmic Ray Neutron Count Rate.

Table 2. Correlations of Solar Activity with Winter Parameters at Ft. Churchill.  
Tabulated values are the most significant correlation\* and lag in days.

PARAMETER	HEIGHT RANGES	0-DAY DIFFERENCES					1-DAY DIFFERENCES					7-15 DAY DIFFERENCES				
		p	$\rho$	T	u	v	p	$\rho$	T	u	v	p	$\rho$	T	u	v
Sunspot No.	Lo						X	X				X	X		X	
	Hi									X						
F10.7	Lo							X							X	
	Hi															X
Magnetic Field	Lo							X								
	Hi															
Temp., Solar Wind	Lo															
	Hi															
Density, Solar Wind	Lo															
	Hi															
Speed, Solar Wind	Lo															
	Hi															
AE Index	Lo						X	X								X
	Hi						X	X						X		
D <sup>st</sup> Index	Lo						X	X		X		X	X	X		
	Hi						X	X	X					X		
Sulfur Mt., CRN	Lo						X	X	X		X					
	Hi				X		X	X	X							
Deep River, CRN	Lo									X						
	Hi				-.36,4						X					X
Alert, CRN	Lo									X						
	Hi				-.35,3						X					X

\*Tabulated values are better than 1% significant, blanks indicate less than 1% significance, X's indicate too few data (<20) for significant correlation.

Table 3. Correlations of Solar Activity with Winter Parameters at Kennedy.

PARAMETER	HEIGHT RANGES	0-DAY DIFFERENCES					1-DAY DIFFERENCES					7-15 DAY DIFFERENCES				
		p	$\rho$	T	u	v	p	$\rho$	T	u	v	p	$\rho$	T	u	v
Sunspot No.	Lo										X					
	Hi						X	X								
F10.7	Lo										X					
	Hi						X	X								
Magnetic Field	Lo															
	Hi										.46,4					
Temp., Solar Wind	Lo															
	Hi										X					
Density, Solar Wind	Lo															
	Hi															
Speed, Solar Wind	Lo															
	Hi															
AE Index	Lo						X	X	X	X	X					
	Hi									X						X
D <sup>st</sup> Index	Lo						X	X	X	X	X					
	Hi										X					-.39,4
Sulfur Mt., CRN	Lo															
	Hi													-.38,7		
Deep River, CRN	Lo															
	Hi													-.33,0		
Alert, CRN	Lo															
	Hi													-.35,0		

Table 4. Correlations of Solar Activity with Winter Parameters at Ascension.

PARAMETER	HEIGHT RANGES	0-DAY DIFFERENCES					1-DAY DIFFERENCES					7-15 DAY DIFFERENCES				
		p	$\rho$	T	u	v	p	$\rho$	T	u	v	p	$\rho$	T	u	v
Sunspot No.	Lo								X							X
	Hi															X
F10.7	Lo															X
	Hi								X							X
Magnetic Field	Lo						X	X		X	X					
	Hi									X	X					
Temp., Solar Wind	Lo								X							
	Hi															
Density, Solar Wind	Lo								X							
	Hi															
Speed, Solar Wind	Lo															
	Hi										X					
AE Index	Lo						X	X							X	X
	Hi								X		X					
D <sup>st</sup> Index	Lo											-.32,10	-.32,10			X
	Hi											-.34,10	-.34,10			
Sulfur Mtn., CRN	Lo								X							X
	Hi				-.44,2											
Deep River, CRN	Lo								X							X
	Hi				-.44,2											
Alert, CRN	Lo		-.41,7					X	X							X
	Hi				-.59,2			X	X	X						

Table 5. Correlations of Solar Activity with Summer Parameters at Three Sites,

SITE	PARAMETER	HEIGHT RANGES	0-DAY DIFFERENCES					1-DAY DIFFERENCES					7-15 DAY DIFFERENCES				
			p	$\rho$	T	u	v	p	$\rho$	T	u	v	p	$\rho$	T	u	v
FT. CHURCHILL	Sunspot No.	Lo						X	X	X	X	X					
		Hi						X	X	X	X	X					
	Magnetic Field	Lo	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Hi	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	AE Index	Lo						X	X	X	X	X	-.50,5				
		Hi						X	X	X	X	X					
	D <sup>st</sup> Index	Lo						X	X	X	X	X					
		Hi						X	X	X	X	X	-.69,-4	-.69,-4			
	Alert, CRN	Lo	-.31,6					X	X	X	X	X					
		Hi						X	X	X	X	X					
KENNEDY	Magnetic Field	Lo	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Hi	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	AE Index	Lo								.45,10							
		Hi															
	Alert, CRN	Lo									-.44,0						
		Hi										-.51,7					
ASCENSION	Magnetic Field	Lo	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Hi	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	AE Index	Lo			.37,7	.41,-5					-.71,10						
		Hi															-.31,1
	Alert, CRN	Lo				-.38,-6		X	X	X	X	X					
		Hi						X	X	X	X	X					

were evaluated versus number of days before or after a flare or boundary crossing. Results such as those shown in Figure 13 are produced. Superposed Epoch analyses were done versus the 0-day, 1-day, and 7-15 day daily differences in pressure, density, temperature, and wind components at the three MRN sites studied. All solar sector crossings (regardless of direction of field change) and all flares of Comprehensive Index  $\geq 9$  were used as key days in separate superposed epoch studies. Threshold levels of other solar parameters (AE index, F10.7 index, sunspot number, etc.) were also selected whereby superposed epoch analyses could be done relative to key days defined by upward crossings of these threshold values.

Many of the superposed epoch analyses indicated significant changes in daily differences before and after the key day. Many also indicated significant differences in mean daily differences on one or more individual days. The significance levels were evaluated on the basis of a t-test comparing difference in 15 day means before and after the key day or individual day means compared to the 15 day mean. In Figure 13, days 2 and 5 were indicated by such a test to have mean daily differences different from the 15 day mean with 1% significance level. However, visual inspection of Figure 13 seems to indicate that this apparent significant difference results not from the values of days 2 and 5 being so much lower than the other values as it does from the fact that the standard deviation about the mean for days 2 and 5 seems, for some reason, to be smaller than for the other days. The visual image of Figure 13 does not present an appearance of significant flare effect, despite the t-test significance result. Similarly, many of the before-and-after significance results seemed to be artificial when examined visually, as in Figure 13 for 0-Day Zonal Wind versus Flares, for which the t-test indicated a 1% significant before/after difference. Because of these anomalies in interpretation of results, all of the superposed epoch analyses of daily differences were discarded, and only the correlation results, discussed above, were used in further analysis and interpretation.

#### Thickness and Circulation Index Results

Correlation analysis of the various solar activity parameters versus 5-0.4 mb thickness and 5 mb and 0.4 mb circulation index were also done. Since the time resolution is one week for the upper air maps from which the

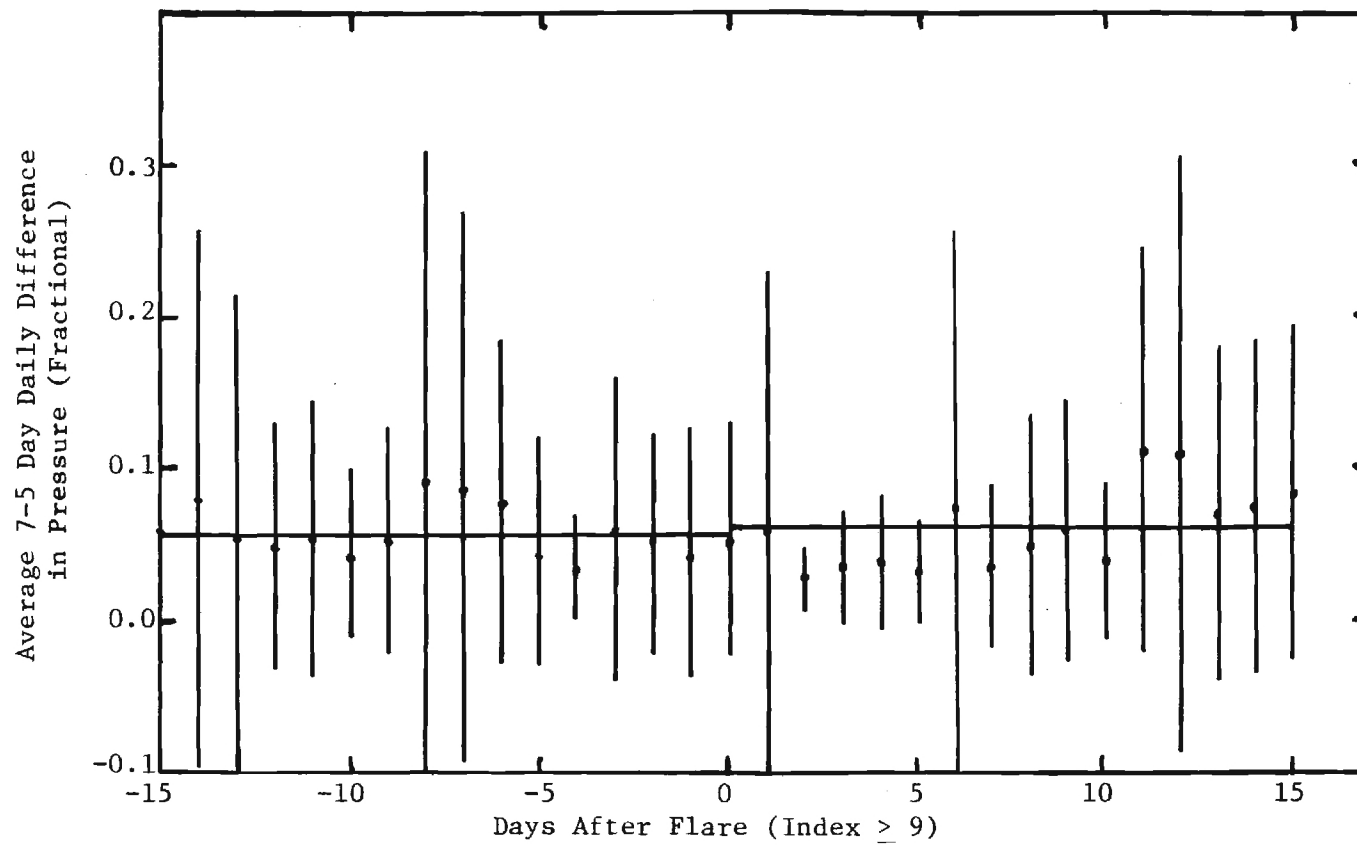


Figure 13. Superposed Epoch Analysis for 7-15 Day Daily Differences in Pressure of Kennedy Versus Days Before or After a Solar Flare of Comprehensive Index  $\geq 9$ .

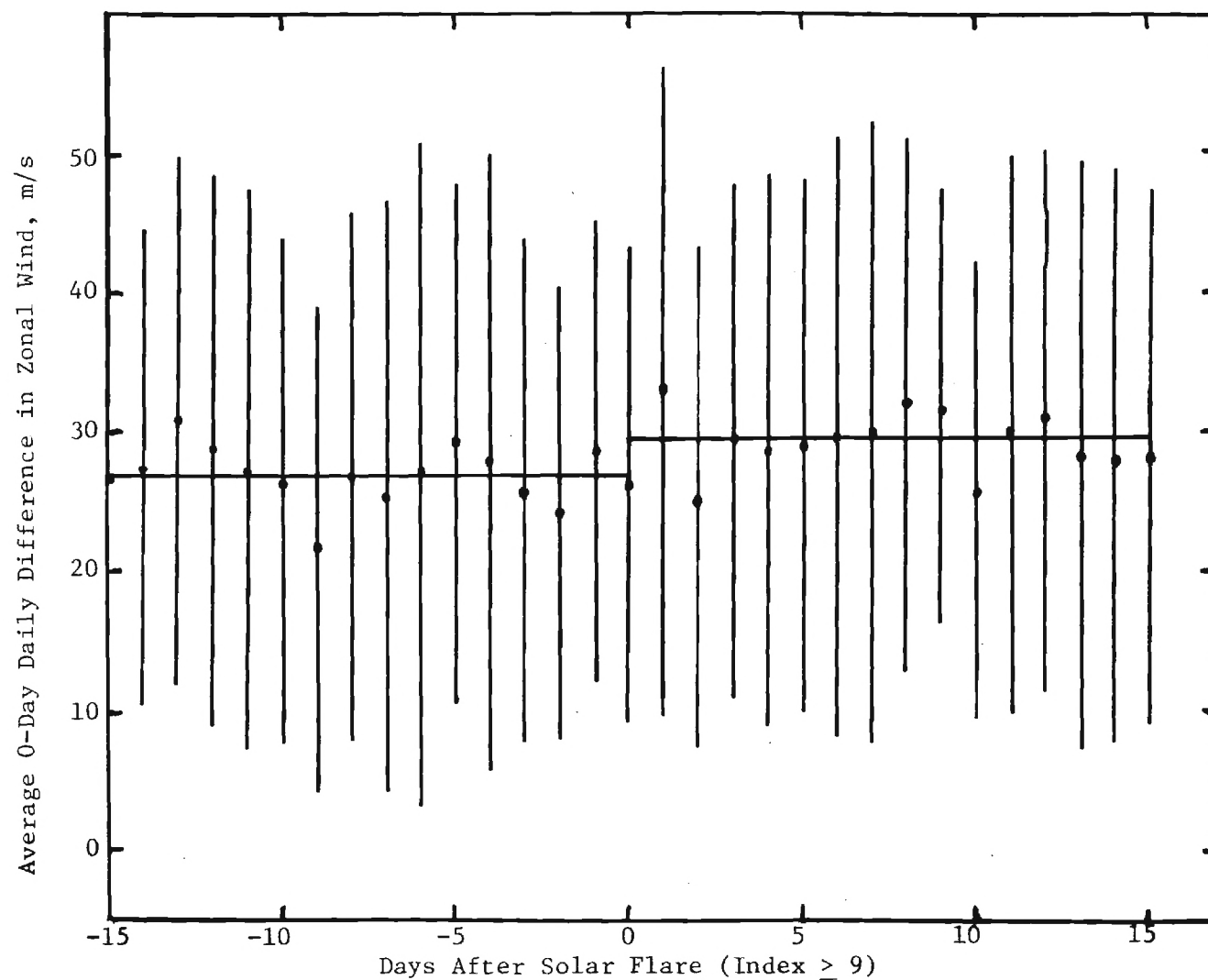


Figure 14. Superposed Epoch Analysis for 0-Day Daily Differences in Zonal Wind at Ft. Churchill Versus Days Before or After a Solar Flare of Comprehensive Index  $\geq 9$ .



circulation and thicknesses are derived, only zero lag correlations were done. An example (of one of the larger magnitude correlations) is shown in Figure 15. This plot shows the weekly average 5-0.4 mb thickness versus weekly averaged solar wind number density ( $\text{cm}^{-3}$ ) for the Fall season (September, October, November).

Results for all of the thickness and circulation index correlation analyses are shown in Table 6-8. In these tables asterisks indicate 1% significance levels, dashes indicate significance level less than 5%, and no symbol indicates 1-5% significance. Correlation values greater than 0.3 in magnitude and better than 1% significance are underlined.

#### Thickness Versus Flare Studies

A special study of possible association of 5-0.4 mb thicknesses with large solar flares was also conducted. These studies allow assessment of the possible effects of heating (increased thickness) or cooling (decreased thickness) of the 5-0.4 mb layer. The seasonal mean thickness for summer and winter were plotted against seasonal number of flares of comprehensive index  $\geq 12$ . These results are shown in Figures 16 and 17.

A superposed epoch analysis of 5-0.4 mb thickness was done for key days defined by flares with index  $\geq 12$ . Results for summer and winter seasons are shown in Figure 18.

The possible effects of the very large flare of August 1972 on 5-0.4 mb thickness were examined by plotting July-September thickness for 1972 and comparing these values with average thickness for July-September of the other years studied. These results are shown in Figure 19.

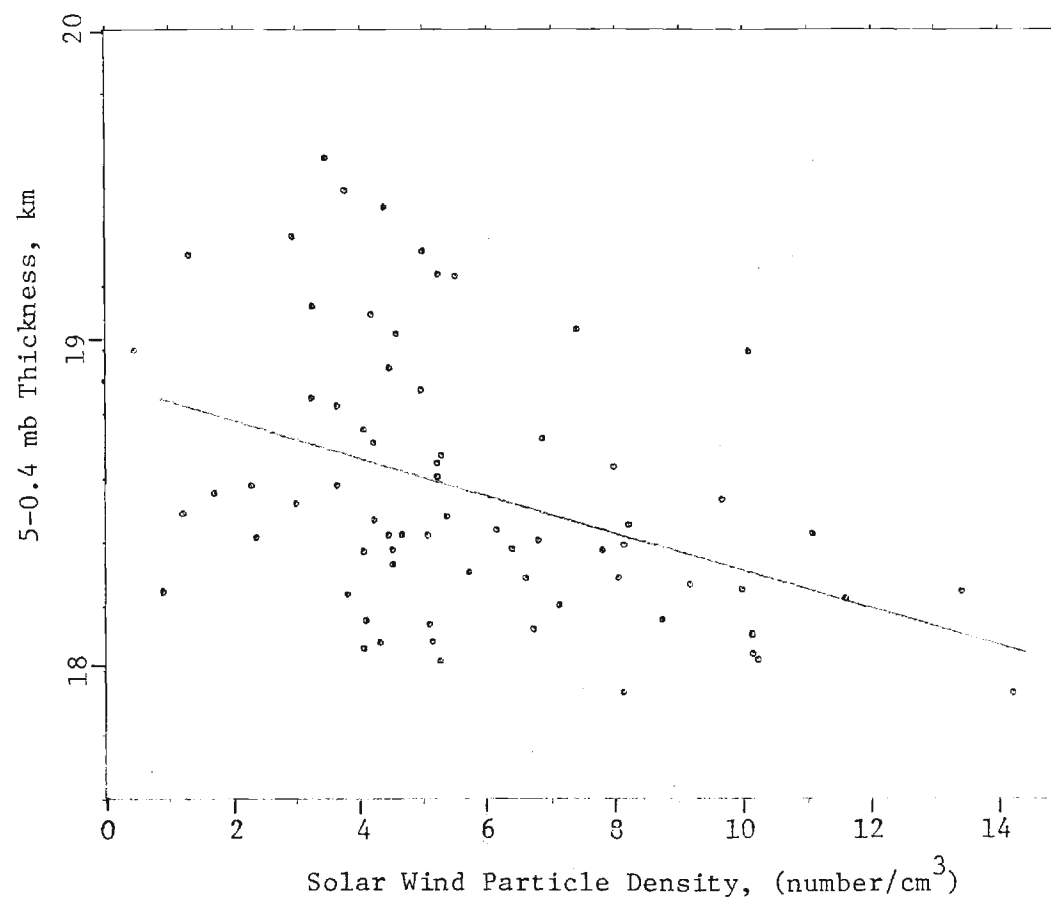


Figure 15. Correlation of Weekly Average 5-0.4 mb Thickness Versus Weekly Average Solar Wind Particle Density for the Fall Season.

Table 6. Correlation of Solar and Geomagnetic Parameters  
with 5-0.4 mb Layer Thickness.

	PARAMETER	WINTER		SPRING		SUMMER		FALL		ANNUAL	
		$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$
Solar Wind	Field Strength	-	-	-.262	6.8	-.268	7.2	-	-	-.152	2.3
	Temperature	-	-	-.268	7.2	-	-	-	-	-.125	1.6
	Density	-	-	-.438*	19.2	-	-	-.415*	17.3	-.369*	13.6
	Speed	-	-	-.262	6.8	-	-	-	-	-	-
Geomagnetic Index	AE Index	-	-	-	-	-	-	-	-	.188*	3.5
	D <sup>st</sup> Index	-	-	-	-	-	-	-	-	-	-
Cosmic Ray Neutrons	Sulfur Mtn.	-	-	-	-	-.379*	14.3	-	-	-	-
	Deep River	-	-	-	-	-	-	-.267	7.1	-	-
	Alert	-	-	-	-	-	-	-.321*	10.3	-.233*	5.4
Solar Activity	Sunspot No.	-	-	-	-	.289*	8.4	.239	5.7	-	-
	F10.7	-	-	-	-	.300*	9.0	.235	5.5	-	-

\* Indicates significance at 1% level; others significant at 5% level; dashes indicate less significant than 5% level.  $r^2$  is % of total variance explained by the correlation.

Table 7. Correlation of Solar and Geomagnetic Parameters  
with 5 mb Level Circulation Index.

	PARAMETER	WINTER		SPRING		SUMMER		FALL		ANNUAL	
		$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$
Solar Wind	Field Strength	-	-	-	-	-	-	-	-	.139	1.9
	Temperature	-	-	-	-	-	-	-	-	.140	2.0
	Density	-	-	-	-	-	-	<u>.353*</u>	12.5	<u>.357*</u>	12.8
	Speed	-	-	-	-	-	-	-	-	-	-
Geomagnetic Index	AE Index	-	-	-	-	-	-	-	-	-.196*	3.9
	D <sup>st</sup> Index	-	-	-	-	-	-	-	-	-	-
Cosmic Ray Neutrons	Sulfur Mtn.	-	-	-	-	-	-	-	-	-	-
	Deep River	-	-	-	-	-	-	-	-	-.121	1.5
	Alert	-	-	-	-	-	-	-	-	.219*	4.8
Solar Activity	Sunspot No.	-	-	.197	3.9	-	-	-	-	-	-
	F10.7	-	-	.221	4.9	-	-	-	-	-	-

\* Indicates significance at 1% level; others significant at 5% level; dashes indicate less significant than 5% level.  $r^2$  is % of total variance explained by the correlation.

Table 8. Correlation of Solar and Geomagnetic Parameters  
with 0.4 mb Level Circulation Index.

	PARAMETER	WINTER		SPRING		SUMMER		FALL		ANNUAL	
		$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$	$\rho$	$r^2\%$
Solar Wind	Field Strength	-	-	-	-	-	-	-	-	.167*	2.8
	Temperature	-	-	-	-	-	-	-	-	.132	1.7
	Density	-	-	.347*	12.0	-	-	.301	9.0	.332*	11.0
	Speed	-.197	3.9	-	-	-	-	-	-	-	-
Geomagnetic Index	AE Index	-	-	-	-	-	-	-	-	-.201*	4.1
	D <sup>st</sup> Index	-	-	-	-	-	-	-	-	-	-
Cosmic Ray Neutrons	Sulfur Mtn.	-	-	-	-	-	-	-	-	-	-
	Deep River	-	-	-	-	-	-	-	-	-.134	1.8
	Alert	-	-	-	-	-	-	-	-	.189*	3.6
Solar Activity	Sunspot No.	-	-	-	-	-	-	-.210	4.4	-	-
	F10.7	-	-	-	-	-	-	-	-	-	-

\* Indicates significance at 1% level; others significant at 5% level; dashes indicate less significant than 5% level.  $r^2$  is % of total variance explained by the correlation.

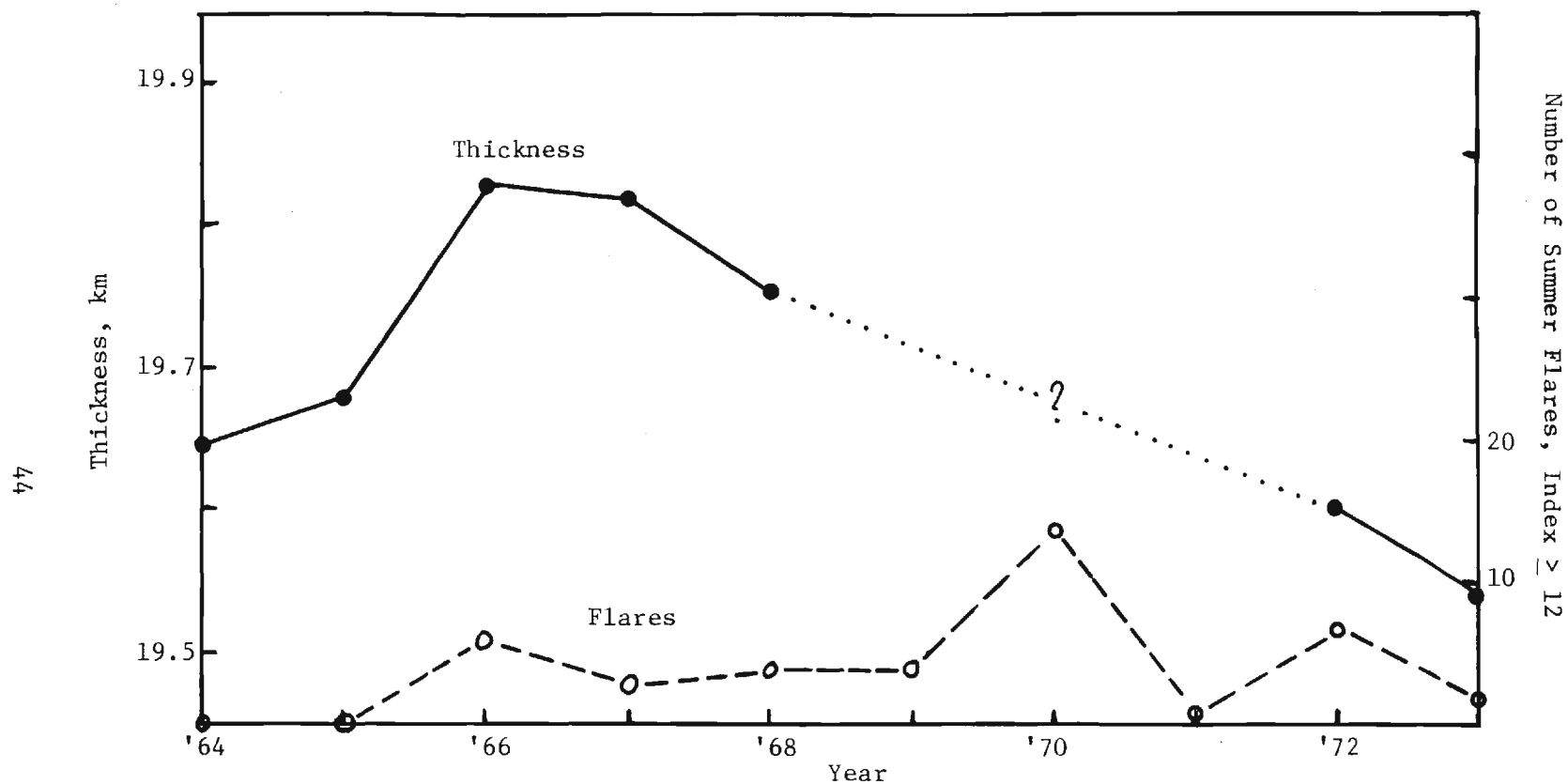


Figure 16. Summer Average 5-0.4 mb Thickness and Number of Summer Solar Flares with Comprehensive Index  $\geq 12$  for 1964-1973.

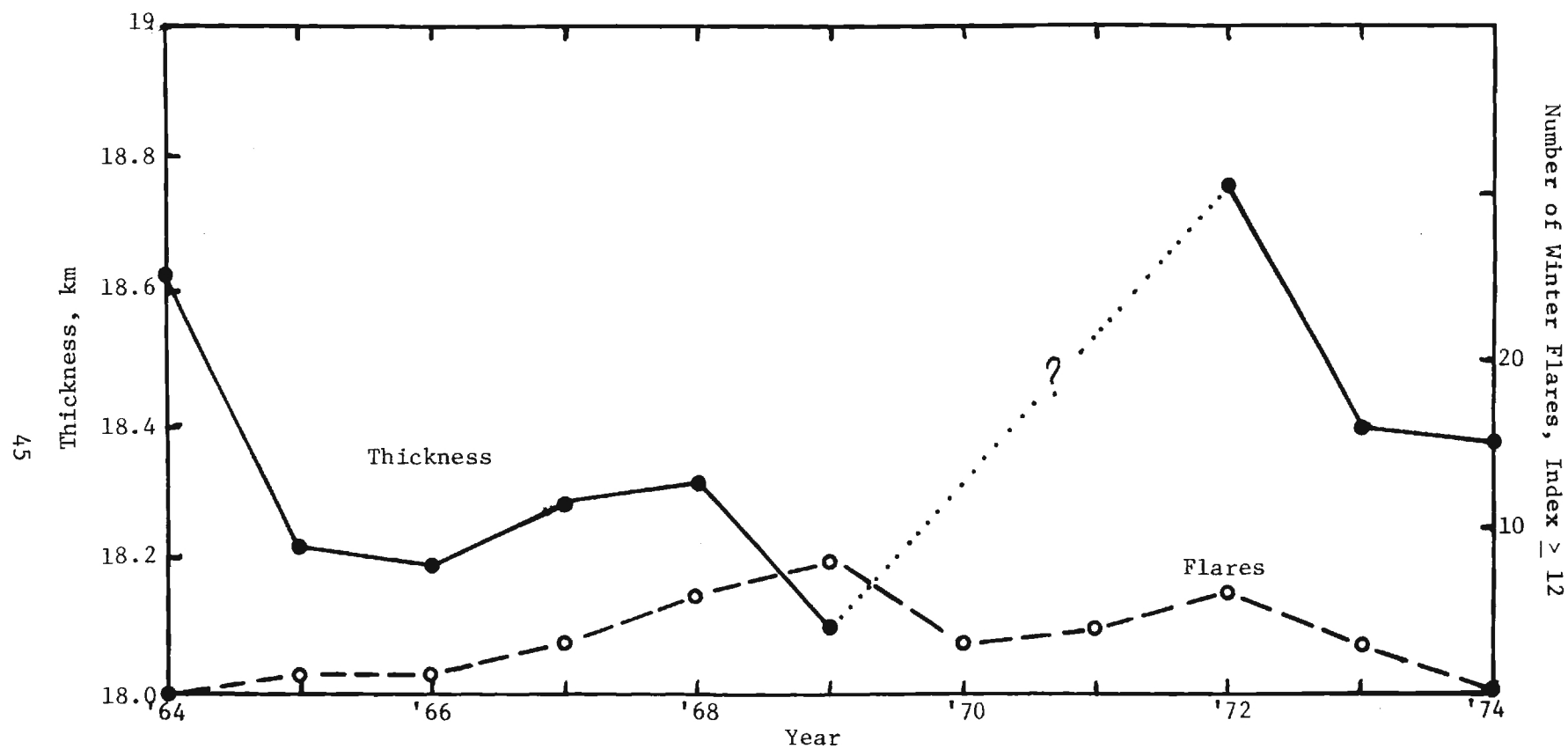


Figure 17. Winter Average 5-0.4 mb Thickness and Number of Winter Solar Flares with Comprehensive Index  $\geq 12$  for 1964-1974.



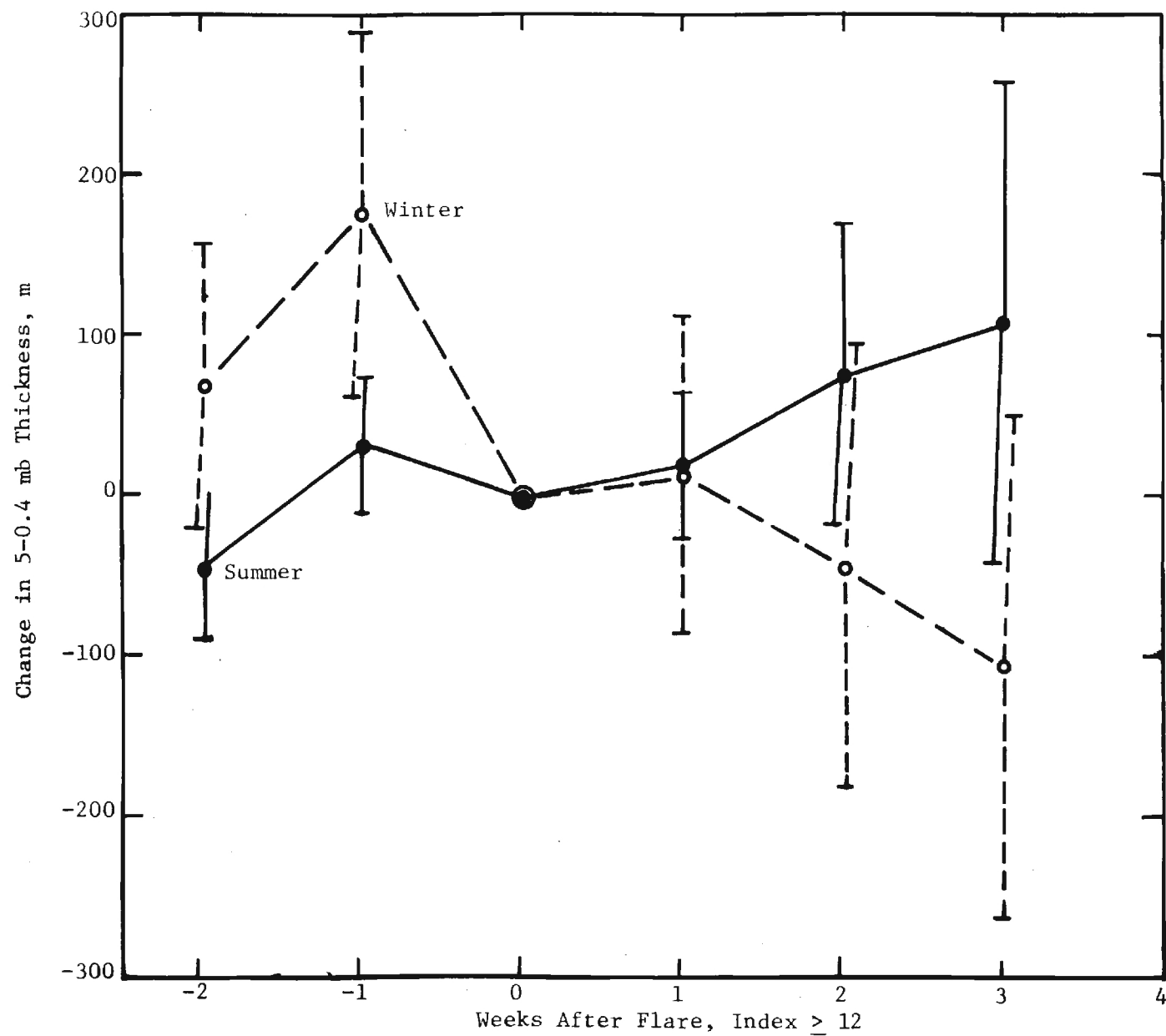


Figure 18. Superposed Epoch Analysis of 5-0.4 mb Thickness Versus Flares of Index  $\geq 12$  for Summer and Winter.

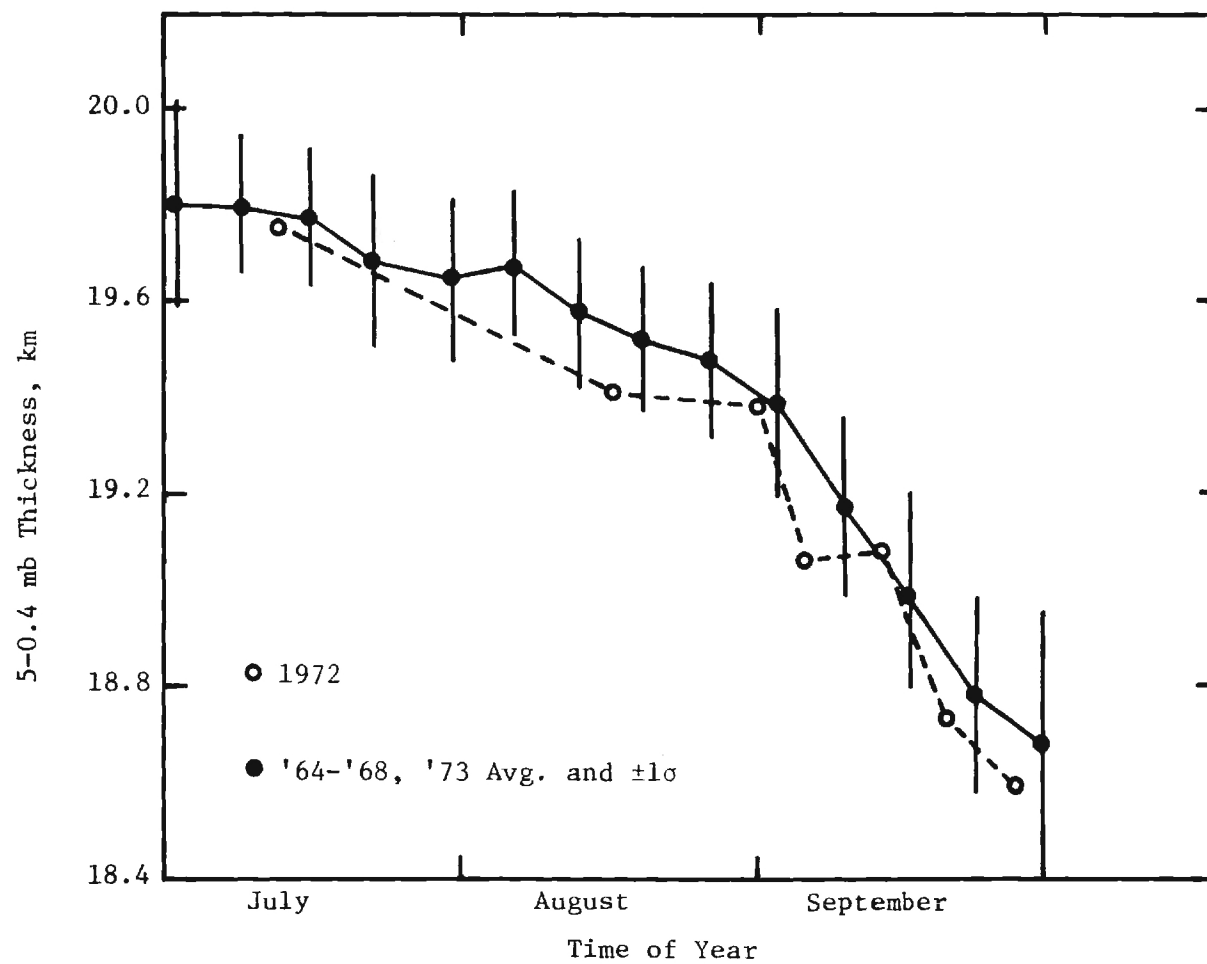


Figure 19. July-September 5-0.4 mb Thickness for 1972 (Year with Large Flare) Versus Average Thickness During Other Years.

#### 4. INTERPRETATIONS AND CONCLUSIONS

Some plausible hypothesis for possible solar activity effects on the upper atmosphere, which can be tested by the data and results of this study are:

- 1) Possible direct atmospheric heating (thickness increases) in the 5-0.4 mb level, through absorption of UV and ozone production processes or heating due to enhanced high energy particle flux (as would explain the results of Ramahrishana and Seshamani, 1973; Seshamani and Ramahrishana, 1978; and Kasimiovskii and Longinov, 1973).
- 2) Possible decreased temperatures (thickness decreases) in the 5-0.4 mb level because of higher Nitric Oxide (NO) production in the upper stratosphere caused by solar flares and by solar cycle variations in cosmic ray produced NO. Temperature decreases in the 5-0.4 mb layer, accompanying temperature increases below the 10 mb level, have been hypothesized by Zerofos and Crutzen (1975).
- 3) Increased perturbations from the climatological mean (0-day differences) due to heating or cooling effects, or propagation of standing waves of pressure such as hypothesized by Volland (1977).
- 4) Increased (or decreased) perturbation by gravity waves (1-day differences) or traveling planetary-scale waves (7-15 day differences). The solar-influenced change in upper atmospheric wave reflection condition mechanism, hypothesized by Hines (1973, 1974) and Hines and Halevy (1975, 1977), would produce larger daily differences in the 25-65 km range if waves are reflected above 65 km, and lower daily differences if the waves are reflected below 25 km.

##### Daily Difference Analysis Results

From the correlation results of Tables 2-5, it is difficult to make a case for any of these particular hypotheses. Of the 1068 correlations tested in the Table 2-5 results, one might expect something on the order of 11 to yield 1% significance levels on a statistical test. Tables 2-5 indicate 27 values with correlation magnitudes greater than 0.3 and with 1% indicated significance level. Of these 27 "significant" correlations, 24 show positive solar activity correlations and 3 show negative solar activity correlations.

Negative correlations for  $D^{st}$  and cosmic ray neutron counts are considered as positive solar activity correlations, since  $D^{st}$  and cosmic rays are inversely related to solar activity. Of the 27 "significant" correlations in Tables 2-5, 19 are at positive lags (meteorological "effect" after solar activity "cause"), 5 are at negative lag, and 3 at 0 lag. On the basis of these numbers, it would seem that there is some small degree of "signal" intermixed with a rather large degree of "noise" in the data.

Of the 27 "significant" correlations in Tables 2-5, 13 are from Ascension (10 positive solar activity correlation, 3 negative; 11 positive lags, 2 negative), 8 are from Kennedy (all 8 with positive solar activity correlations and either 0 or positive lag), and only 6 are from Churchill (3 with positive lag, and 3 with negative lag). These numbers would indicate that, contrary to many studies and hypotheses which indicate solar activity influence predominantly at high latitudes, the major "effects" seen at the altitudes studied here are at equatorial latitudes.

Heating or cooling effects due to solar activity phenomena should be indicated by significant 0-Day Temperature correlations with solar activity parameters. However, only 1 "significant" 0-Day Temperature correlation is found (out of 82 possible values). Volland's hypothesized solar variation effect on pressure should show up as 0-Day Pressure correlations with larger effects at high latitudes and little or no effect at low latitude (due to the latitude variation of the Rossby-Haurwitz waves which he suggests are excited by the solar variations). Only 2 "significant" correlations of 0-Day pressure or density are found, however (one with positive lag, one with negative).

The largest numbers of "significant" correlations in Tables 2-5 are for the 0-Day Wind correlations and the 7-15 Day Pressure or Density correlations (both of which have 7 total, all with positive solar activity correlations, 5 with positive lags, 2 with negative lags). Of the 7 0-Day Wind correlations, 5 are from Ascension (but 2 of these have negative lags; 3 have positive lags). Of the 7 7-15 Day Pressure or Density correlations, 4 are from Ascension (all with positive solar activity correlation and positive lag) and 3 are from Churchill (one positive lag, 2 negative lag).

The distribution of "significant" correlations in Tables 2-5 among the solar activity parameters is of some interest. There is only one for sunspots,

F10.7, magnetic field, or solar wind parameters, but 13 for AE or  $D^{st}$  index and 13 for cosmic ray count. Of the 13 AE/ $D^{st}$  "significant" correlations, 11 have positive solar activity correlations, 2 have negative; 10 have positive lags and 3 have negative lags. Of the 13 cosmic ray "significant" correlations, 12 are positive solar activity correlations, 1 negative, and 11 are 0 or positive lags and 2 negative lags.

One possible interpretation of these results is that the meteorological parameters of the upper stratosphere and mesosphere show no relation to solar activity at all but exhibit relations only with parameters affected by the meteorology of lower layers. The AE and  $D^{st}$  indices, although related to auroral electrojet and ring current activity which have a solar influence component, could also be influenced through upward transport of energy from the troposphere (Hines, 1973). The cosmic ray neutron count, although barometrically corrected to remove air mass variations, could also have a residual influence from the meteorology of the lower atmosphere. Correlations with geomagnetic indices, but not solar parameters is also consistent with the results of Nastrom and Belmont (1976) for this height region.

#### Thickness and Circulation Results

Comparison of seasonal average 5-0.4 mb thicknesses from Figures 16 and 17 with large flare occurrence (in the same figures) or with sunspot number (Figure 4) or F10.7 (Figure 3) indicates that there is no apparent significant relation between the solar cycle and 5-0.4 mb thickness. However, this conclusion would be more defensible if thickness data were available for the peak solar activity years 1969-1971.

The special thickness versus flare study results of Figures 18 and 19 do not lend support to the Zerefos-Crutzen model of cooling in the upper stratosphere due to ozone loss from increased NO production. Figure 18 shows no significant increase or decrease in summer or winter 5-0.4 mb thickness (i.e., mean temperature) following major flares. Figure 19 shows somewhat lower thicknesses (temperatures) in 1972, the year of the large August solar flare. However, the 1972 values are generally within the  $\pm 1\sigma$  error bars about the average for the other years--indicating no really significant effect.

Of the thickness or circulation index correlations in Tables 6-8, the most significant would appear to be those for: 1) thickness versus solar wind density (spring, fall, and annual, but not summer and winter) with a negative

solar activity correlation (i.e., stratospheric cooling indicated associated with solar activity), and 2) the thickness versus cosmic ray correlations (summer at Sulfur Mountain, fall at Alert), with a positive solar activity correlation (i.e., negative cosmic ray correlation, since cosmic rays are inversely related to solar activity). These results are contradictory. Also contradictory are the results that AE,  $D^{st}$  and cosmic rays produce the more "significant" correlations in Tables 2-5 while solar wind density produces the more "significant" correlations in Tables 6-8. The solar wind density correlations with thickness in Table 6 are in agreement with the cooling hypothesis of Zerefro and Crutzen, but the cosmic ray results in Table 6 support the idea of upper stratospheric heating associated with solar activity.

As with the daily difference analysis, the thickness and circulation data in Tables 2-6 indicate a larger number of "significant" correlations (9 out of 165 with magnitude  $\geq 0.3$  and better than 1% significance) than would be expected.

### Conclusions

The results presented here do not show clear evidence in support of any of the physical processes hypothesized. Indeed, certain of the results are contradictory (thickness/circulation results compared to daily difference results, for example). Both types of analysis do show more than the expected number of "significant" correlations however, indicating a possible weak effect in the rather large "noise" of the data.

It would be very helpful for further clarification of the results here if similar analysis could be done which include thickness and circulation data in the periods 1969-1971, unavailable for these studies, and in which the maximum occurred for the solar cycle being examined in this study. It could also be significant that the solar cycle examined here (1964-1974) was the least active one since the 1923-1933 period.



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